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Integrated climatic impacts of forestry and fibre-based packaging

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The purpose of this study was to examine the integrated climatic impacts of forestry and the use fibre-based packaging materials. The responsible use of forest resources plays an integral role in mitigating climate change. Forests offer three generic mitigation strategies; conservation, sequestration and substitution. By conserving carbon reservoirs, increasing the carbon sequestration in the forest or substituting fossil fuel intensive materials and energy, it is possible to lower the amount of carbon in the atmosphere through the use of forest resources. The Finnish forest industry consumed some 78 million m^3 of wood in 2009, while total of 2.4 million tons of different packaging materials were consumed that same year in Finland. Nearly half of the domestically consumed packaging materials were wood-based. Globally the world packaging material market is valued worth annually some €400 billion, of which the fibre-based packaging materials account for 40 %.

The methodology and the theoretical framework of this study are based on a stand-level, steady-state analysis of forestry and wood yields. The forest stand data used for this study were obtained from Metla, and consisted of 14 forest stands located in Southern and Central Finland. The forest growth and wood yields were first optimized with the help of Stand Management Assistant software, and then simulated in Motti for forest carbon pools. The basic idea was to examine the climatic impacts of fibre-based packaging material production and consumption through different forest management and end-use scenarios. Economically optimal forest management practices were chosen as the baseline (1) for the study. In the alternative scenarios, the amount of fibre-based packaging material on the market decreased from the baseline. The reduced pulpwood demand (RPD) scenario (2) follows economically optimal management practices under reduced pulpwood price conditions, while the sawlog scenario (3) also changed the product mix from packaging to sawnwood products. The energy scenario (4) examines the impacts of pulpwood demand shift from packaging to energy use. The final scenario follows the silvicultural guidelines developed by the Forestry Development Centre Tapio (5). The baseline forest and forest product carbon pools and the avoided emissions from wood use were compared to those under alternative forest management regimes and end-use scenarios. The comparison of the climatic impacts between scenarios gave an insight into the sustainability of fibre-based packaging materials, and the impacts of decreased material supply and substitution.

The results show that the use of wood for fibre-based packaging purposes is favorable, when considering climate change mitigation aspects of forestry and wood use. Fibre-based packaging materials efficiently displace fossil carbon emissions by substituting more energy intensive materials, and they delay biogenic carbon re-emissions to the atmosphere for several months up to years. The RPD and the sawlog scenarios both fared well in the scenario comparison. These scenarios produced relatively more sawnwood, which can displace high amounts of emissions and has high carbon storing potential due to the long lifecycle. The results indicate the possibility that win-win scenarios exist by shifting production from pulpwood to sawlogs; on some of the stands in the RPD and sawlog scenarios, both carbon pools and avoided emissions increased from the baseline simultaneously. On the opposite, the shift from packaging material to energy use caused the carbon pools and the avoided emissions to diminish from the baseline. Hence the use of virgin fibres for energy purposes, rather than forest industry feedstock biomass, should be critically judged if optional to each other. Managing the stands according to the silvicultural guidelines developed by the Forestry Development Centre Tapio provided the least climatic benefits, showing considerably lower carbon pools and avoided emissions. This seems interesting and worth noting, as the guidelines are the current basis for the forest management practices in Finland.

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Tämän tutkimuksen tarkoituksena on tarkastella metsien käytön ja kuitupohjaisten pakkausmateriaalien yhdistettyä ilmastovaikutusta. Metsien vastuullisella käytöllä on tärkeä rooli ilmastonmuutoksen hillitsemisessä. Metsien avulla pystytään hillitsemään ilmastonmuutosta erilaisin suojelu, hiilensidonta ja hiilen korvaus strategioiden avulla. Nämä keinot perustuvat hiilivarastojen suojeluun, hiilensidonnan lisäämiseen sekä materiaalien substituution, kun energiaintensiivisiä materiaaleja ja fossiilisia energialähteitä korvataan puulla. Näin hiilidioksidin määrää ilmakehässä voidaan laskea. Suomalainen metsäteollisuus kulutti vuonna 2009 noin 78 miljoonaa kuutiota puuta. Samaan aikaan Suomessa kulutettiin yhteensä 2,4 miljoonaa tonnia erilaisia pakkausmateriaaleja. Liki puolet näistä pakkauksista oli puupohjaisia. Maailmanlaajuisesti koko pakkausmateriaalimarkkinat ovat vuotuiselta arvoltaan noin 400 miljoonaa euroa, joista kuitupohjaisten pakkausmateriaalien osuus on 40 %.

Tutkimuksen teoreettinen viitekehys perustuu metsikkötason tasaisen muuttumattoman tilan analyysiin, puuston kasvusta ja tuotoksista. Puustotiedot koottiin Metlan tietokannoista, ja ne koostuivat yhteensä 14:sta Etelä- ja Keski-Suomessa sijaitsevasta metsikkökoealasta. Metsiköiden kasvut ja tuotokset optimoitiin Stand Management Assistant ohjelmiston avulla, jonka jälkeen ne simuloitiin Motti-metsikkösimulaattorissa. Perusideana oli tutkia kuitupohjaisten pakkasmateriaalien käytön ilmastovaikutuksia, vaihtoehtoisten metsänkasvatusten ja loppukäyttöskenaarioiden avulla. Metsänomistajan taloudellinen optimikasvatus valittiin tutkimuksen perusuraksi (1). Vaihtoehtoisissa skenaarioissa kuitupohjaisten pakkausmateriaalien tarjonta laskee perusurasta. Laskenut kuitupuun kysyntä (LKK) skenaario (2) seuraa metsänkasvatuksessa taloudellista optimia, alennetulla kuitupuun hinnalla. Tukkipuuskenaariossa (3) metsänkasvatus on sama kuin LKK:ssa, mutta myös lopputuotteiden keskinäiset suhteet muuttuvat, kysynnän siirtyessä pakkauskuiduista sahatavaraan. Energiaskenaariossa (4) metsäkasvatus seuraa perusuraa, mutta kysyntä siirtyy pakkauskuiduista puun energiakäyttöön. Viimeinen skenaario seuraa metsänkasvatuksessa Tapion (5) hyvän metsänhoidon suosituksia. Ideana on vertailla perusuran hiilivarastoja sekä puutuotteiden kautta saavutettuja vältettyjä päästöjä, vaihtoehtoisten skenaarioiden hiilivarastoihin ja päästöihin. Vertailun avulla selvitetään kuitupohjaisten pakkausmateriaalien merkitystä ilmastolle, ja vähentyneen tarjonnan vaikutusta hiilidioksidivarastoihin ja päästöihin.

Tutkimuksen tulokset osoittavat kuitupohjaisten pakkasmateriaalien käytön olevan suotavaa, kun asiaa tarkastellaan ilmastonäkökohdista. Kuitupohjaiset pakkasmateriaalit korvaavat tehokkaasti energiaintensiivisempiä materiaaleja ja hidastavat biogeenisen hiilen palautumista ilmakehään. LKK ja tukkipuuskenaariot pärjäsivät kummatkin vertailussa hyvin. Nämä skenaariot tuottivat suhteessa enemmän tukkipuuta, jonka avulla pystytään välttämään tehokkaasti kasvihuonekaasupäästöjä ja hidastamaan hiilen vapautumista takaisin ilmakehään hyvinkin pitkäksi aikaa. Tulokset viittaavat siihen, että muuttamalla metsiköiden kasvatusta nykyisestä, voisi olla mahdollista kasvattaa metsien että tuotteiden hiilivarastoja, sekä vältettyjä päästöjä yhtäaikaisesti. Kysynnän siirtyminen pakkausmateriaaleista energiakäyttöön sen sijaan laski sekä hiilivarastoja ja vältettyjen päästöjen määrää perusurasta. Jos nämä käyttötarkoitukset ovat materiaalin niukkuuden takia toisensa poissulkevia, tulisi neitsytkuitujen polttamiseen suhtautua kriittisesti, ja mieluummin käyttää raaka-aine metsäteollisuustuotteiden valmistukseen. Metsien kasvatus Tapion hyvän metsänhoidon suositusten mukaan pärjäsi vertailussa huonosti, tarjoten kaikista skenaarioista vähiten ilmastohyötyjä. Tämä on huomionarvoista, sillä nykyinen metsänhoito Suomessa perustuu pitkälti juuri näihin suosituksiin.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Forests and climate change

Climate change is one of the worst environmental threats ever faced by the mankind. The greenhouse gas concentration in the atmosphere is currently at its highest levels in at least the last 650000 years. Greenhouse gas is a gas in the atmosphere that absorbs and re-emits radiation within the thermal infrared range, thus causing warming in the surrounding atmosphere. Ever since the beginning of the industrial revolution, and especially within the last one hundred years, the concentration has rapidly increased as a result of fossil fuel combustion, from approximately 280 ppm in the late 1800s to 388 ppm in 2010. At the same time the average global surface temperature has increased by approximately 0.76 °C, while 15 of the warmest years in the temperature record have been recorded in the past 20 years. The warmer earth will have an impact on the earth's climate, climate variability and the ecosystems in many and partly unpredictable ways. Some regions could even benefit from the warmer more favourable climate, while other regions would suffer from catastrophic environmental changes (Ryan et al. 2010). The estimates on the speed of climate change vary, but even in the most optimistic scenarios, the average temperature of earth would increase by some 1.8 °C by 2100 (Statistics Finland 2011a).

Out of several greenhouse gases that contribute to climate change, the most prominent is carbon dioxide (CO_2), which mainly results from the combustion of fossil fuels. Forests sequestrate CO_2 from the atmosphere during their lifetime and thus play an integral role in mitigating climate change. In Finland the forests grew by an estimated 100 million m^3 in 2009, vastly surpassing the total drain, a trend which has persisted ever since the 1970s. At the same time the forests cover some 26 million ha or 86 % of all land area in Finland (Finnish Forest Research Institute 2010). In comparison, the global forest coverage in 2005 was about 3952 million ha or just 30 % of all the world's land area (IPCC 2007). The forests themselves, with their growing forest stocks, increased the net carbon sinks in Finnish forests to some 49 $TgCO_2eq$ in 2009, equal to about 74 % of Finnish greenhouse gas emissions that year (Statistics Finland 2011b). In its totality the carbon pool in living forest biomass is estimated to be globally in the range of 1000 $GtCO_2$ (IPCC 2007), over 15000 times the amount of annual CO_2 emissions of Finland. Even after felling, the carbon remains captured within the woody materials, such as sawlogs used for construction or pulpwood used for paper and packaging. After their respective lifecycles, the wood waste is recycled, incinerated (with or without energy recovery) or land-filled, at which point some or all of the carbon is release back to the atmosphere at varying rates.

In addition to carbon sequestration, forests mitigate climate change also by providing a sustainable source for raw materials. This flow of raw material can be used for different wood-based products, which can substitute for other more fossil energy intensive materials, such as plastics and metal, or when wood is used for energy purposes, oil and natural gas. Because of the avoided fossil emissions, the greenhouse gas concentration in the atmosphere is decreased. It is estimated that for example in the United States, forests and forest products offset some 12 – 19 % of all US fossil fuel emissions, though largely owing to forest recovery from the past deforestation and extensive harvesting (Ryan et al. 2010).

In 2009 the greenhouse gas emissions in Finland decreased by 5.8 % from the previous year, to 66.3 $TgCO_2eq$, about 7 % under the Kyoto Protocol target of 71 $TgCO_2$ (Statistics Finland 2011b). The energy sector is especially vital in reaching the target, as in 2008 it was responsible for approximately 78 % of all the emissions (Finnish Forest Research Institute 2010). With approximately 5.2 Tg of fossil fuel based CO_2 emissions, the Finnish forest industry was responsible for approximately 33.9 % of the total emissions, that resulted from manufacturing or 7.5 % of all emissions in Finland. This is negligible however, compared to the total energy consumed by the industry, as 21.6 Tg of biogenic CO_2 emissions came from the use of renewable wood fuels used by the forest industry. Incidentally, the Finnish forest industry self-provides a vast portion of the energy that it consumes. With black liquor and over 20 million m^3 of wood used for energy purposes, a fifth of the total energy consumption of 1336 PJ in Finland comes from wood. The largest share of the energy consumed in Finland still comes from fossil fuels, namely oil, coal and natural gas, which accounted for 46 % of the total energy consumption in 2009.

With different forest management and end-use strategies, come tradeoffs. If the carbon pools in the growing forest stocks were to be increased, by lengthening the rotation periods, the supply of roundwood would decrease, at least on the short-term. Because of material substitution, this in turn could lead to the use of more energy intensive materials instead. Similarly if pulpwood was used for energy purposes, instead of paper or packaging manufacturing, the decreased amount of paper and packaging would be substituted by some other materials. These various tradeoffs play an important role in the decision making process. For instance, avoiding deforestation and increasing the harvesting intervals to increase the forest carbon pools, could move timber production elsewhere, thus leading to no total net benefits for the carbon in the atmosphere (Ryan et al. 2010).

In western Europe approximately 75 Tg of materials were used for packaging purposes in 1995 (Hekkert 2001). This constitutes for approximately 10 % of the total quantity of Western European material markets. Furthermore around 20 % of all timber consumption in Europe is used for wooden pallets and packaging, with around 400 million wooden pallets produced each year in Europe alone. The sector represents approximately 4 % of all European Union woodworking industries, with estimated 3000 companies employing some 50000 people (Finnish Forest Industries 2010). The overall environmental impact of the packaging sector is enormous. It is estimated that for example in 1994, the greenhouse gas emissions associated with the packaging materials in Western Europe, were some 144 TgCO_2eq, which at the time equalled to 14 % of all material-related greenhouse gas emissions or 3.3 % of all greenhouse gas emissions in Europe (Hekkert 2001). In Finland the total consumption of packaging materials in 2008 was some 2.4 Tg (PYR 2010).

1.2 Sustainable forestry

In 1993 at the Second Ministerial Conference on the Protection of Forests in Europe (MCPFE) in Helsinki, sustainable forest management (SFM) was defined as *“... the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems*.” (MCPFE 1993).

After the main idea and the underlying concepts for sustainable forest management were first agreed upon at the Helsinki Conference, the more precise criteria and the indicators for SFM were developed in the follow-up meetings in Geneva and Antalya in the mid-1990s. Based on the developed framework, two reports were compiled, first in 1998 for the third MCPFE in Lisbon, and then in 2003 for the fourth MCPFE in Vienna, where the pan-European indicators were revised, based on the experiences since the Lisbon meeting. The first national sustainability indicators for Finland were developed early on in 1996, based on the precursory pan-European work. They were revised in 2000, and further in 2007, when the third national indicators were introduced, based on the national experiences, on-going international deliberations, and the agreed upon pan-European indicators. The national SFM criteria closely follow pan-European criteria laid out in 2003, however with slight alterations. The criteria include forest resources, health and vitality of the forest ecosystem, productive functions of forests, biological diversity, protective functions and also socio-economic aspects of forests (Ministry of Agriculture and Forestry 2007).

1.3 Packaging materials

Packaging can be seen as a socio-scientific discipline, with multiple functions and roles which it simultaneously has to fulfil (Lockhart 1997). The paramount goal for packaging is to ensure the delivery of goods to the consumer, in the best possible condition intended. Most importantly it should protect, preserve and contain the product, especially during the transportation phase. It should also provide information to the consumer, regarding the product, and serve as a device for marketing. Packaging simultaneously operates in human, physical and atmospheric environments, which are inseparable from each other. The three environments each have three functions, which also have to be fulfilled, and they are neither separable from each other, nor then three environment. The functions of a package are protection, utility and communication. The interacting functions and environments can be presented in the so-called packaging matrix. The exact composition of the packaging matrix varies depending on the application, and the intended use of the package, however its' generic form is presented in Figure 1.

Environments		Packaging Functions		
		Protection	Utility	Communication
	Human	Tamper evident features Child resistance features Designs that do not require scissors or knives to open	Reclosable designs Easy to open designs Pre measured units Compliance packaging (packaging that, by nature of its design, helps people comply with medication regimens) Talking packages Material Shape Configuration Texture	Brand name Warnings Directions Expiration dates Storage information Graphics Material Shape Color Configuration Texture Photographs Text
	Biospheric	Amber Color to protect from UV damage UV Absorbers to protect from UV damage Water Vapor Barriers Oxygen Barriers to protect from oxidation Oxygen absorbers to protect from oxidation Antimicrobial films to retard microbial degradation Water Vapor barrier to protect from Moisture Loss or Gain Wet Strength Corrugated	Controlled atmosphere packaging Modified atmosphere packaging Edible films Wet strength corrugated	Time and temperature indicators Pictorials
	Physical (Distribution Channels)	Cushioning Shipping containers Corner posts Air bags Materials with Adequate compression strength to withstand stacking	Stretch wrap Shrink wrap Self heating packages Self cooling packages Freezer to oven capable Handles for carrying Appropriately sized cases	"This side up" "Fragile" Bar Codes Radio frequency identification "Handle with care" "Temperature not to exceed 70 degrees Fahrenheit" Pictorials Accelerometers

Figure 1. Packaging matrix (Bix et al. 2003).

Packaging can be further divided in to three basic categories, based on their intended use and purpose. These categories are primary, secondary and tertiary (Figure 2) (Järvi-Kääriäinen and Ollila 2007, p.10). Primary packaging directly wraps or contains the product and is typically the smallest unit of distribution or use, whereas the secondary package is used to wrap the primary package. An example of secondary package would be a display-ready corrugated container for juice cartons, the juice cartons being the primary package for the liquid inside. The tertiary package is used to wrap or contain both primary and secondary packages, and it is especially designed for bulk-handling in the warehousing and transportation phase. For this reason tertiary packages are usually pallets, in the form of unit loads, for ease of handling, and they are designed in a way, that they can be easily handled by machinery. From the material perspective, the categories are somewhat arbitrary in the sense that the material use is not bound by the categories in any strict sense, as several different materials can potentially be used, and the materials can often substitute for each other. Furthermore, the packaging materials are seldom used singly, rather they are used jointly. For instance many liquid packaging systems are made from liquid packaging board with high-density polyethylene caps and aluminium pull tabs.

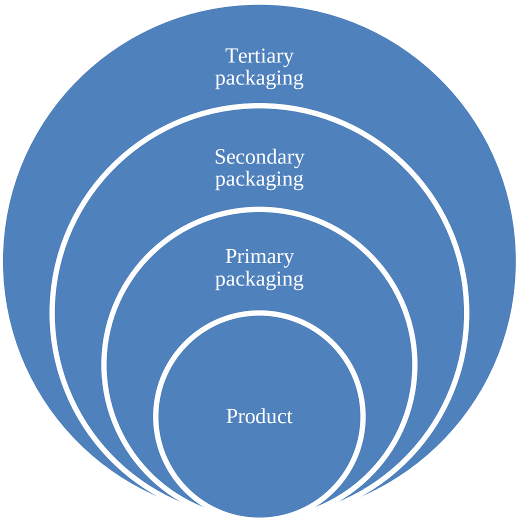

Figure 2. Packaging layers.

Some commonly used packaging materials are glass, plastic, paper, paperboard, metal and wood. In Finland the most common packaging material, defined by its weight, is wood, closely followed by metal (Table 1). In total, over 2.4 Tg of different packaging materials were domestically consumed in 2008 (PYR 2010). It should be noted that the total use is not the same as the virgin material use. The total use is calculated as the sum of new materials entering the market, which also includes recycled and reused materials. The total consumption of paper, paperboard and corrugated board packaging was 0.27 Tg, while the consumption of wood packages, namely pallets, was 0.91 Tg. Wood and fibre-based packaging materials account for some 48 % of all packaging material consumption, or two-thirds of all virgin packaging materials placed on the market, with approximately half of this consumed by the food packaging industry.

Table 1. Total consumption of packaging materials in Finland in 2008 (PYR 2010).

Material	Quantity placed on the market, tons	Reuse, tons	Total use, tons
GLASS	60 645	114 795	175 440
PLASTICS	115 373	251 778	367 150
PAPER, BOARD AND CORRUGATED BOARD	256 074	10 101	266 175
METALS	50 807	654 028	704 835
WOOD	217 205	689 344	906 549
OTHERS	695	1 109	1 804
TOTAL	700 799	1 721 155	2 421 953

The value of paper processing and the fibre- and wood-based packaging industry's production in Finland is over €1 billion annually. The sector is an important employer, as these activities provide employment for some 5600 people in Finland. The total value of the entire packaging industry's production in Finland is about €2 billion, while the global market for the packaging industry is worth some €400 billion annually. Fibre-based packaging, which includes corrugated board, carton and liquid packaging board, accounts for approximately 40 % of this (Finnish Forest Industries 2011).

The global packaging market was valued at nearly $480 billion in 2005, with Asia emerging as the biggest consumer of packaging materials in the future (World Packaging Organisation, 2008). The biggest national packaging markets are found in the United States, Japan, China, Germany and France. Measured by the value, clearly the most important packaging material in the world is fibre-based packaging, with worldwide sales exceeding $180 billion in 2005. Behind fibre-based packaging comes plastic, metal, glass and other materials, in the respective order. The "other materials" sector is principally composed of wooden pallets and containers, which is noteworthy, as this means almost 6 % of all global packaging material consumption is in the form of either wooden pallets or containers. The fastest growing packaging material sector is the rigid and flexible plastics. This is mainly due to rising demand for PET bottles, and plastics substituting for metals, glass and sometimes fibre-based materials. The growing importance of the food markets and the rising demand for ready-meals and other convenience-oriented products, has also been kind for the plastic demand. Both metal and glass are expected to lose market share in the future to fibre-based packaging and plastics.

1.4 Sustainable packaging

Sustainability can be defined as resource consumption that maximizes the welfare of the current generation, without compromising the welfare of the future generations. Packaging materials have a significant impact on the welfare of the current and future generations, as they can affect the environment in an adverse way, as a result of landfilling, consumption of scarce resources, and the greenhouse gas emissions that result from the manufacturing and use of packaging materials (Gielen and Moriguchi 2001).

There are no clear-cut criteria to what constitutes a sustainable package. The Sustainable Packaging Coalition (SPC) developed in 2009 a framework for measuring the sustainability of packaging materials. In their Sustainable Packaging Indicators and Metrics Framework (Sustainable Packaging Coalition 2009), they discuss several key elements, definitions and performance categories, to what should constitute a sustainable package. Greenhouse gas emissions are just one of the many indicators, in the SPC framework that provides information about the package's sustainability. According to the SPC definition, the key elements in sustainable packaging are that it

- is beneficial, safe & healthy for individuals and communities throughout its life cycle;
- meets market criteria for both performance and cost;
- is sourced, manufactured, transported, and recycled using renewable energy;
- optimizes the use of renewable or recycled source materials;
- is manufactured using clean production technologies and best practices;
- is made from materials healthy in all probable end of life scenarios;
- is physically designed to optimize materials and energy;
- is effectively recovered and utilized in biological and/or industrial closed loop cycles

The consumption of packaging materials leads to greenhouse gas emissions through the production and transportation, and through the end-of-life management of the materials. The most important greenhouse gas emission related to packaging is carbon dioxide (CO_2), however in the case of landfilling, the methane (CH_4) emissions have to be considered as well. Methane emissions result from the decomposition of woody materials in the landfills, and CH_4 has 25 higher global warming potential than carbon dioxide. Recycling of packaging materials is essential in order to lower the greenhouse gas emissions, as recycling generally results in considerably less emissions, than would results from the production of packaging from virgin materials. For example in the case of aluminium, the emissions from recycled secondary aluminium are 10 – 20 times lower than the emissions from primary aluminium. Both improved material management, such as finding substitution benefits in materials and increasing the recycling and reuse, as well as reduction of emissions in production and waste management, show potential in reducing the packaging related environmental impacts. The costs for material efficiency improvements are considerably lower than the costs for emissions reductions in material production. Packaging materials have technical potential, as well as low lifecycle costs of material efficiency improvement, compared to many other mitigation tactics, and thus packaging materials should be paid more attention in climate change policy and discussion in general (Hekkert 2001).

According to International Trade Administration of the U.S. Department of Commerce (ITA 2010), the strive for cost reductions, changing consumer attitudes and the legislation, are the three major forces driving the industry and the packaging supply chains towards greater sustainability nowadays. In their assessment it is currently especially the European laws, regulations and standards, which are actively and foremost shaping the global packaging market in terms of sustainability.

1.5 Packaging waste, material recovery and reuse in Europe

Approximately half of the paper consumed in Europe is manufactured by using recycled fibres. The most recycled fibre is used in producing packaging materials and newspaper paper grades. The Finnish forest industry each year uses approximately 0.75 Tg of recovered paper as a raw material. This equals to about 5 % of all raw material use. The relatively small share is explained by the fact that almost all production is exported, and subsequently recovered outside of Finland. Importing recycled fibres back to Finland is not, at least at the moment, seen as an economically viable option (Finnish Forest Industries 2011).

The Environmental Registry for Packaging (PYR) is a non-profit company responsible for compiling the annual statistics of packaging material recovery, reuse and recycling in Finland, in accordance to the EU Commission Decision 2005/270/EC on packaging and packaging waste. The statistics are collected from packagers, fillers, importers, exporters, material producers and recovery organisations, and they cover 95% of all packaging materials entering the Finnish markets. In 2008 (Table 2) the total use of packaging materials in Finland was roughly 2.4 Tg (PYR 2010).

Table 2. Use, reuse, recovery and recycling of packaging materials in Finland (PYR 2010).

Material	Quantity placed on the market, tons	Recovered by recycling as material, tons	Recycling rate, %	Reuse, tons	Reuse rate, %	Total use, tons
GLASS	60 645	48 391	80	114 795	65	175 440
PLASTICS	115 373	26 175	23	251 778	69	367 150
PAPER, BOARD AND CORRUGATED BOARD	256 074	238 468	93	10 101	4	266 175
METALS	50 807	38 294	75	654 028	93	704 835
WOOD	217 205	42 996	20	689 344	76	906 549
OTHERS	695	0	0	1 109	62	1 804
TOTAL	700 799	394 324	56	1 721 155	71	2 421 953

According to European Commission decisions (Commission Decision 2005/270/EC), the waste generated by packaging in Finland is deemed to be equal to the packaging placed on the Finnish market. The quantity placed on the market represents the first-time use of any given packaging material. When a reusable package enters the market for the first time, it is presented under the quantity placed on the market. After the first lifecycle the package is refilled or reused after cleaning, and it is then presented under the reuse. With recovery and reuse, the total amount of packaging materials is calculated as the sum of reused and one-way packaging materials. According to the Environmental Register of Packaging (PYR 2010) statistics, in 2008 the recovery rate for all packaging materials in Finland was nearly 90 %. This means that a majority of packaging materials entering the Finnish market were collected and either recycled or incinerated at the end of their lifecycle. In its entirety only about 0.07 Tg of packaging waste was disposed to the landfill sites, which is a mere 3 % of the total packaging use. The reuse rate for packaging materials in Finland is 71 %, one of the highest in the European Union. The recycling rate for packaging materials is 56 %, about the European Union average and just slightly above the recycling target set by European Union Packaging and Packaging Waste Directive (Directive 94/62/EC). The average recovery rate in European Union in 2008 was 71% (Figure 3).

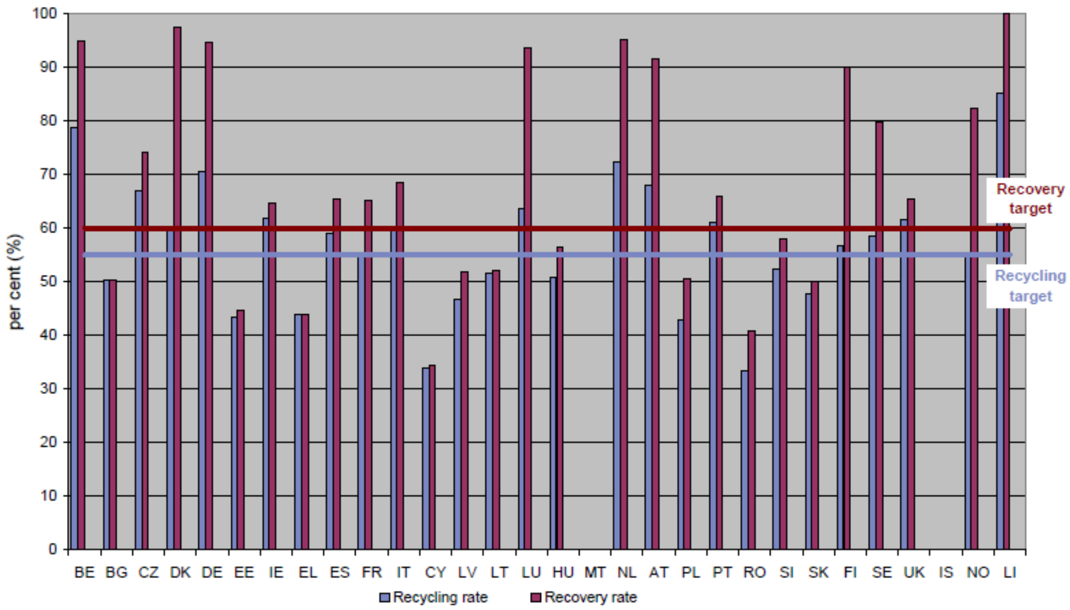

Figure 3. Recycling and recovery rates of packaging waste in EU in 2008 (Eurostat 2011).

The targets for recovery and recycling set by the Packaging Waste Directive (Directive 94/62/EC) are that

a) no later than 30 June 2001
    a. between 50 % as a minimum and 65 % as a maximum by weight of packaging waste will be recovered or incinerated at waste incineration plants with energy recovery
    b. between 25 % as a minimum and 45 % as a maximum by weight of the totality of packaging materials contained in packaging waste will be recycled with a minimum of 15 % by weight for each packaging material
b) no later than 31 December 2008
    a. 60 % as a minimum by weight of packaging waste will be recovered or incinerated at waste incineration plants with energy recovery
    b. between 55 % as a minimum and 80 % as a maximum by weight of packaging waste will be recycled
    c. the following targets for materials contained in packaging waste must be attained
        i. 60 % for glass, paper and board
        ii. 50 % for metals

iii. 22.5 % for plastics
iv. 15 % for wood

The Commission has also laid out a legally binding Waste Framework Directive (Directive 2008/98/EC) for its' Member States, in which it presents the European waste hierarchy (Figure 4). The hierarchy lays down the generic principles and the priority order to what constitutes the best overall environmental options in waste management. Preventing and reducing the waste at the source is seen as the most favoured option, whereas disposal to landfills and incineration without energy recovery is frowned upon. Reuse is preferred to recycling, as it thought to require and consume less energy and resources. Incineration with energy recovery is considered only better to disposal.

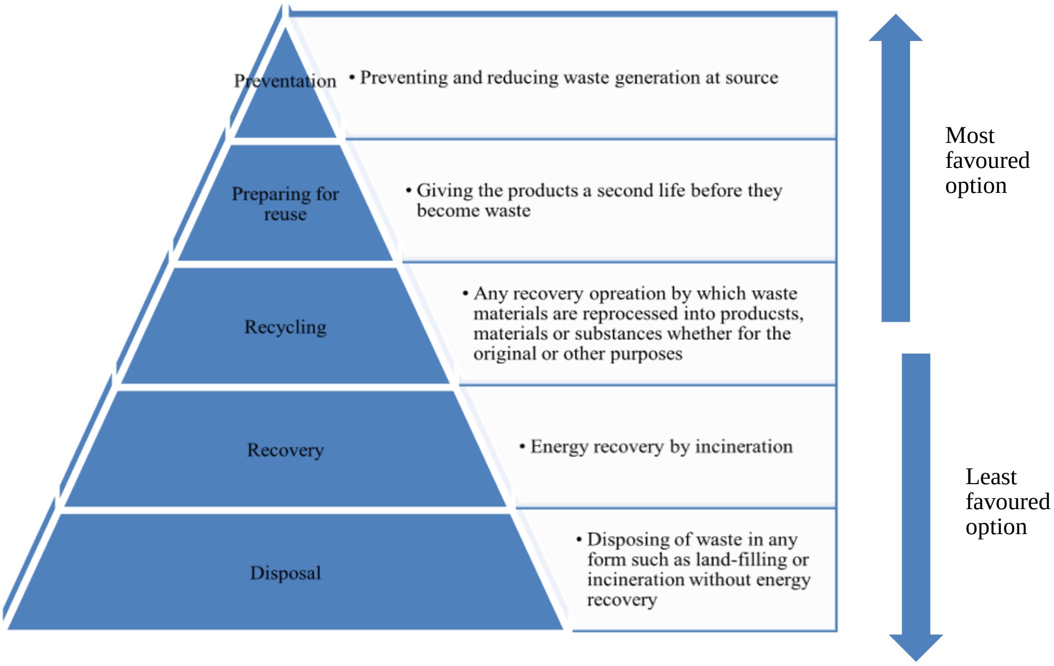

Figure 4. European waste hierarchy.

1.6 Purpose of the study

The purpose of the study is to examine the integrated climatic impacts of forestry and the fibre-based packaging materials. This is examined as a difference between two levels of production and consumption, when the amount of fibre-based packaging material on the market decreases from the current state – the baseline.

While forest and forest product carbon pools and material substitution has been studied in the past, the specific integrated climatic impacts of forestry and fibre-based packaging material use have been neglected, despite the important role of fibre-based packaging as material that can possibly help to mitigate climate change. The lack of knowledge about this specific aspect has been the main motivation in undertaking the study. In this study, the current level of wood material use for fibre-based packaging is evaluated by comparing it to a lower level of use. Therefore, different scenarios are generated to compare and see what kind of climatic impacts using less fibre-based packaging materials could have, weighing the positives and negatives.

The main research questions, for which answers are sought for, are the following:

- The combined carbon pools of forests and wood-based products in different scenarios
    - How important are fibre-based packaging materials for the carbon pools?
    - How long-lived are these carbon pools?
    - When and how is the carbon released back to the atmosphere?
    - How does recycling affect the carbon pools?
- CO_2 emissions of the fibre-based packaging materials over their whole lifecycle
    - How large are the CO_2 emissions?
    - How do the CO_2 emissions compare to other materials such as plastics?
    - What are the functional carbon displacement factors for fibre-based materials?
    - How does the end-of-life management affect the emissions?
    - What is the typical lifespan for packaging materials in Finland?
- Material substitution
    - What are the avoided emissions from material substitution?
    - How do the possibilities to use wood change between scenarios?
    - Should wood raw material resources be allocated to packaging materials rather than something else?

Reliable results from the study would be interesting policywise, especially as the benefits of energy wood use are discussed, as well as from the point of view of the industry, as the results could be used for product marketing and research and development. The results could also justify wood raw material use for fibre-based packaging manufacturing in general, if there are positive climatic impacts to be found in allocating the resources to packaging materials, instead to other uses. The inclusion and comparison of economically optimal forest management practices and forest management by silvicultural guidelines developed by the Forestry Development Centre Tapio will also be interesting, as they are the basis for the current forest management practices in Finland.

2 FORESTRY AND WOOD USE IN FINLAND

2.1 Sustainable forest management in Finland

Based on the principles of the pan-European sustainability indicators and the application of the six national Sustainable Forest Management (SFM) criteria discussed in chapter 1.2, some observations can be made about sustainable forest management in Finland and the state of the Finnish forests. In total, 12 descriptive and 35 quantitative indicators in six different categories are used to measure the sustainability of forest management. The six national and pan-European criteria (Ministry of Agriculture and Forestry 2007) are

1) Maintenance and appropriate enhancement of *forest resources* and their contribution to global carbon cycles.
2) Maintenance of forest ecosystem *health and vitality*.
3) Maintenance and encouragement of *productive functions* of forests.
4) Maintenance, conservation and appropriate enhancement of *biological diversity* in forest ecosystems.
5) Maintenance and appropriate enhancement of *protective functions* in forest management.
6) Maintenance of other *socio-economic functions* and conditions.

The qualitative indicators for forest resources (1) include both the preservation and the increase of forest land, as well as the maintenance of carbon balance in the forests. This is measures by the forest area, the growing stock, the age structure of the forest, the carbon stock of the forest and the use of wood based fuels. Through net growth of the forests, the net annual carbon sink in Finnish forests grew to 49 $TgCO_2$ in 2009. The share of wood based fuels was around 20 % of the total energy consumption in Finland (Finnish Forest Research Institute 2010). The Finnish forest area has remained almost unchanged for the past 40 years, whereas the volume of the growing stock has increased by over 40 % (Ministry of Agriculture and Forestry 2007).

The health and vitality of the forest (2) is measured by the amount of air pollutants, the chemical soil condition, defoliation and forest damage. The health and vitality of

Finnish forests has been relatively good, for example the nitrogen and sulfur deposition loads, most of which come from abroad, have decreased considerably since the 1980s (Ministry of Agriculture and Forestry 2007).

The productive functions (3) of forests are measured by indicators related to both the wood and non-wood aspects of the forests. For example the annual increment and drain are important components of this criterion. Thanks to sustainability promoted by both private forest owners and the government, the annual increment of Finnish forests has constantly surpassed the drain (Finnish Forest Research Institute 2010).

Biological diversity (4) is measured by a large number of indicators such as the tree species composition, forest regeneration, the amount of natural forests and the threatened forest species. In many ways this criterion is very similar to the second criterion of forest health and vitality. In general the Finnish forests have been managed ecologically for decades and under the statutory requirements of the Forest Act since 1997. The endangerment of certain forest species has slowed down since the 1990s (Finnish Forest Research Institute 2010).

The protective functions of forests (5) are mostly focused in the northern parts of Finland, in an area of approximately 3.3 million hectares, as very little problems related to soil erosion, avalanches and shifting exist in Finland. Issues concerning the water systems are however given a special attention in the national criteria, and it has received its' own indicator of "impacts of forest management on waters", which does not exists as such in the pan-European criterion. In general the level of water protection in Finland has constantly improved at felling site and natural peatlands are not drained anymore (Ministry of Agriculture and Forestry 2007).

Finally, the socio-economic functions of forests (6) cover a vast range of different indicators which are related to the maintenance of economic viability of forestry, improvement of employment and occupational safety in the forest sector, safeguarding the opportunities of the public for participation, education and research in forestry and the maintenance of cultural and spiritual values of forests. Despite losing some of its importance since the 1980s, the forests have remained highly important to the Finnish national economy and especially to the imports. In social and cultural sense the Finnish forests also play an important role in shaping the Finnish national identity and the relationship to nature (Finnish Forest Research Institute 2010).

2.2 Use of wood raw material in Finland

In 2009 the total consumption of roundwood in Finland was 59.5 million m^3, of which 7.3 million m^3 were imported roundwood (Finnish Forest Research Institute 2010). The consumption of roundwood declined for the third year in a row, and by 18 % from the year before, while the amount of imported roundwood declined even more sharply by 50 %. Incidentally 2009 was the slowest year for the roundwood markets and timber trading in Finland in the past 25 years. The trend was mostly due to the global recession that had started from the United States in 2007, and its negative impact on the economic climate and consequently the demand of wood-based products, but also due to the large timber stocks at the time.

The majority of the consumed roundwood, 51.5 million m^3, was used by the forest industry. The rest of the wood raw material was consumed for energy purposes at heating- and power plants and small-sized residential houses. Contrary to the declining trend in domestic and imported roundwood consumption, energy wood use increased by one quarter to 8.0 million m^3. In addition to roundwood, the industry used approximately 6.4 million m^3 of sawmill chips and dust, that were generated as industry by-products and wood residue from harvesting and manufacturing. The majority of the by-products and wood residue were consumed for energy purposes, as 12.1 million m^3 of wood was used by heating- and power plants and for fuel wood by small residential houses. In total some 18.5 m^3 of wood by-products and wood residue were consumed. All this added up to approximately 57.8 million m^3 of wood consumed by the forest industry and 20.2 million m^3 of wood used for energy purposes in Finland in 2009 (Figure 5).

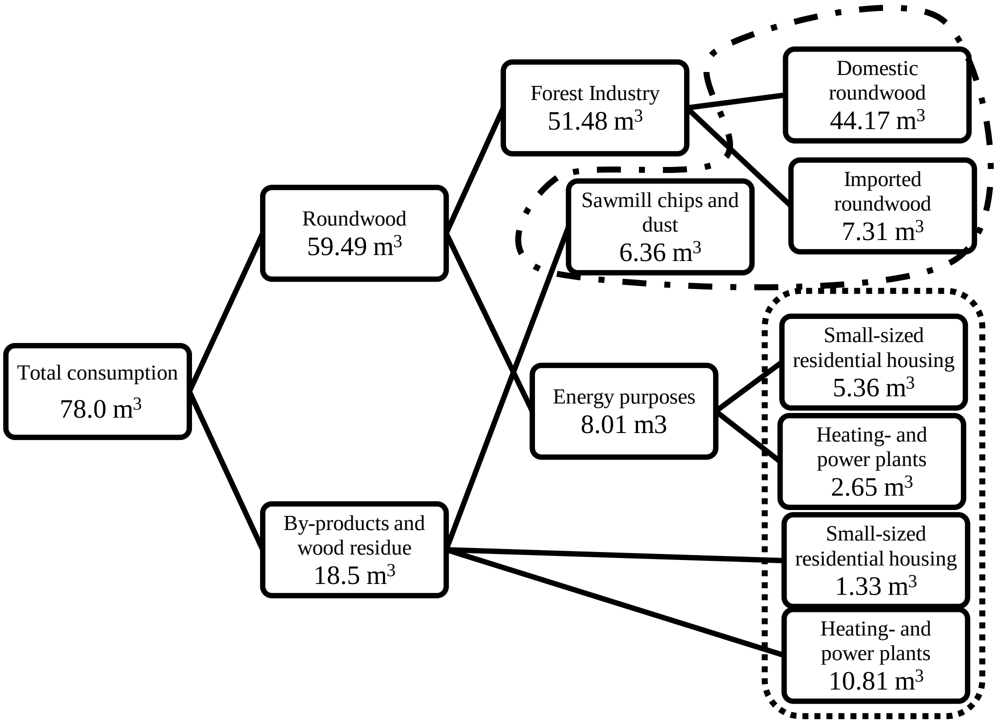

Figure 5. Wood consumption in Finland 2009 (Finnish Forest Research Institute 2010).

The single most important source of consumption for wood raw material in Finland remains the pulp industry with approximately 30.7 million m^3 of roundwood and 6.1 million m^3 of industry by-products and wood residue used in production. The breakdown between mechanical, semi-chemical and chemical pulp is roughly so that three quarters of the wood is used for chemical pulping and the remaining amount for mechanical, with negligible amounts also going in to the semi-chemical production. The second most important sector of the industry is the wood products, with roughly 21.1 million m^3 of wood consumed, namely by the sawmilling industry. Aside from the sawmilling and the plywood and veneer industry, very little wood is used for other purposes by the industry. Rest of the wood, roughly 20.2 million m^3, is used for energy purposes. The production consequently follows the wood consumption. The production was down in 2009, with total production of 10.6 million tons of paper and paperboard, 8.0 million m^3 of sawnwood and 0.8 million m^3 of plywood, with most of the production exported. The total production of paperboard, which includes the packaging materials, was 2.5 million tons with approximately 90 % of the production going in to exports (Finnish Forest Industries 2011).

2.3 Future trends in wood use

The European Union RES-directive (Directive 2009/28/EC) mandates that by 2020 the share of renewable energy should be at least 20 % of the total energy consumption in all the Member States. The specific targets vary between the Member State, in Finland's case the share of renewables being 38 % of all energy. In primary energy this translates in to approximately 39 TWh (Finnish Forest Research Institute 2010). Half of the increment in the renewable energy is expected to come through the increased use of wood chips. This means that by 2020, approximately 12 – 13 million m^3 of wood chips would be used for energy purposes.

Hetemäki and Hänninen (2009) have estimated that the Finnish forest industry wood consumption will decline in the coming years. They base this estimation on three factors that affect the industry; the so-called "China Syndrome", which moves production as well as consumption to developing countries in Asia, electronic substitution of paper media which globally affects the forest sector, and the biological characteristics of Finnish forests, due to which the Finnish forests produce considerably less wood compared to some other countries with more favorable conditions for wood production. For the wood consumption they estimate that by 2020, it declines by 22.9 million m^3 or 30 % from the levels of 2007. The consumption of domestic wood would decline by 21 % or 12.4 million m^3. This would mean an increased potential for energy wood use, as according to the estimates, there would be over 3.0 million m^3 of excess wood chips and dust, as well as approximately 7.1 million m^3 of excess pulpwood available to the market compared to the 2007 levels. The central idea is that in the future the Finnish forest sector is more and more relied on the renewable energy aspect of wood use, rather than the wood-based products. From the economic or environmental point of view, they argue that there is no reason to limit pulpwood outside of the energy use. In the future the stumpage price development would be increasingly attributable to the value added of the energy sector, rather than the forest sector and its wood-based products. At the present the increased use of wood fuels is more restricted by its price and availability, rather than the industrial capacity to utilize it (Pöyry 2010).

In a Government Institute for Economic Research assessment, Honkatukia and Simola (2011) reached a somewhat different conclusion on the future outlook of the

Finnish wood consumption. They argue the previous estimates have been somewhat too pessimistic, but also note that the many uncertainties surround the Finnish forest industry and its future, makes predicting the future difficult. Most strikingly they expect the total consumption of wood to reach some 90 – 100 million m^3 by 2020, due to the forest and energy sector integration. The integration would stem from the climate and energy policies, and the increased use of renewable energy. The consumption of wood is not expected to reach the full industrial potential, which they estimate to be around 80.0 million m^3. The reasons are market-based, and the weak cost competitiveness of the forest industry. In their assessment, the worst-off sector is the paper industry, whereas the future for the paperboard industry looks much brighter. Even in their most pessimistic estimate, the wood consumption would not decline as much as Hetemäki and Hänninen (2009) predicted. They also note that despite the increased consumption of wood, in none of the scenarios the consumption reaches levels, which would threaten the principles of sustainable forest management in Finland.

3 FOREST AND FOREST PRODUCT CARBON POOLS

3.1 Forest carbon cycle

Plants absorb CO_2 from the atmosphere (Gross primary production, GPP), converting it through photosynthesis in to carbohydrates, which the plants can then use to build organic matter such as leaves, wood, and roots. Through autotrophic respiration (R_a) of the plant, some of the CO_2 is released back to the atmosphere. With no outside disturbances the net difference between photosynthesis and the respiration determines the net accumulation of carbon in the plant (Net primary production, NPP). About half of the assimilated CO_2 is used for growth and the maintenance respiration, and it is lost back to the atmosphere, while the other half remains captured within the plant (Gower 2003).

As a result of harvesting forests for wood raw material, it is also important to consider the industrial carbon cycle of forests. The trees are felled, and wood is transported from the forests to different production facilities. The carbon in wood remains captured in wood and paper products, and is eventually released back to the atmosphere when the product is recycled, incinerated or land-filled as waste at the end of their lifecycle. Secondary greenhouse gas emissions also occur in between, as the material is transported and manufactured in to wood-based products at different production facilities (Figure 6). In addition to harvests, disturbances such as forest fires, insects, pathogens, and wind can affect the forest carbon cycle. Even with no disturbances, some of the forest carbon is eventually released back to the atmosphere, as trees grow, shed dead branches, leaves and roots, or simply die. Micro-organisms decompose the dead material, releasing some of the CO_2 back to the atmosphere, while a portion remains captured within the soil. Live and dead trees in mature forests contain approximately 60 % of the carbon in the forest, while the remaining 40 % is captured in the soil and the forest litter (Ryan et al. 2010).

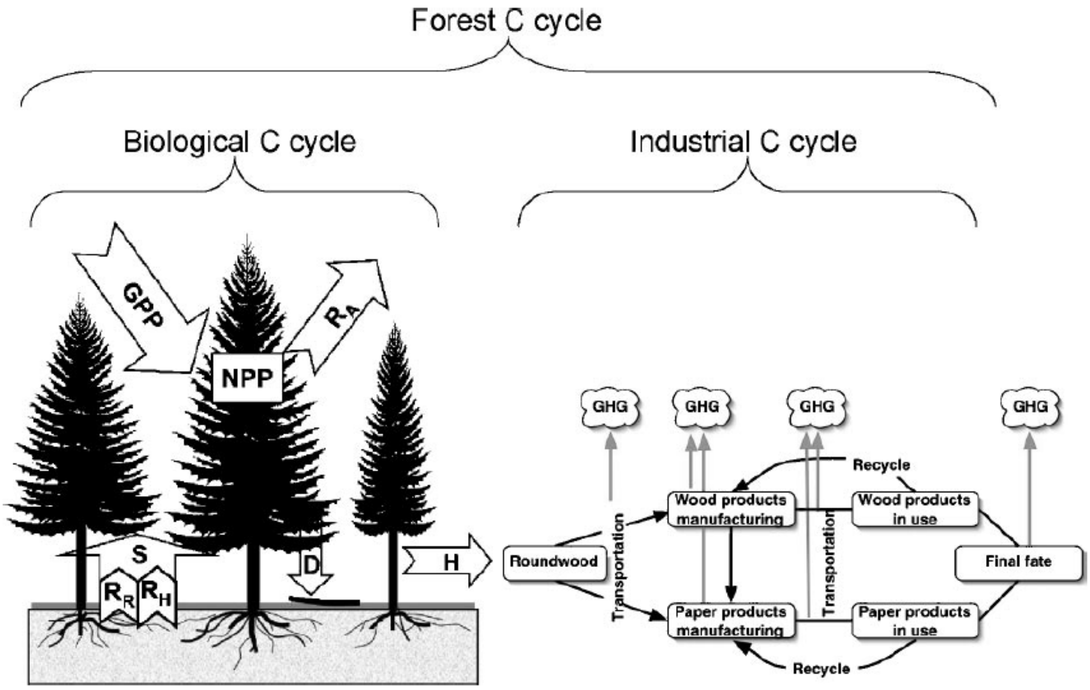

Figure 6. Forest carbon cycle (Gower 2003).

The total carbon pool of the world's forests is estimated to be some 3400 $GtCO_2$, of which approximately 30 % is in the living tree biomass, while the rest is in the dead trees, litter and the soil (FAO 2006, IPCC 2007). In Finland it is estimated that the carbon pool in living tree biomass is approximately 2.3 $GtCO_2$, while the boreal forest soil carbon pool is about 3.8 $GtCO_2$. Compared to forests, the peatland carbon pool is massive and estimated to be some 17.6 $GtCO_2$ (Kauppi et al. 1997). The net carbon sink in the growing forest stock in Finland increased to an all-time high of 49 $TgCO_2eq$ in 2009 (Statistics Finland 2011b). Meanwhile the global greenhouse gas emissions resulting from human activities have reached an all time high of 30.6 $GtCO_2eq$ in 2010 (International Energy Agency 2011).

Buchanan and Levine (1999) emphasize the importance of the balance between the biological and industrial carbon cycles. The carbon released from the wood products can be balanced by the replanting and the regeneration of the forest. Sustainability can only be reached through actions which balance the removals of wood, and the growth of the forest. Only when the growth equals or exceeds the removals, the forest carbon pools can maintain a long-term equilibrium or ideally increase. A sustainably managed forest is carbon neutral in the long-run, as the carbon released following the logging of one stand, is replaced by the carbon absorbed by the growth of the next stand.

Depending on the age of the stand, forests can either be carbon sources or carbon sinks. To increase the forest carbon pools, the forest needs to produce an increasing amount of biomass. Once forests reach maturity or when a steady-state forest management is implemented, the forests carbon pools stop growing. Song and Woodcock (2003) have estimated that a forest stand in the Pacific Northwest of the United States can be a carbon sink for up to 200 years, while peaking in rate of carbon sequestration at the age of 30 – 40 years. Old growth forests are typically considered neutral to the carbon pools, and for any particular year after their maturity, the stands can be either weak sinks or sources for carbon, depending on their heterotrophic respiration (R_h), which is the decomposition of dead stems, leaves and branches on the soil. Luyssaert et al. (2008) however note, that despite the long-standing view of carbon neutrality of old-growth forests, their results indicate that forests can continue to accumulate carbon, and maintain a positive balance even as long as up to 800 years. In Finland some 80 % of trees are conifers, of which little under two-thirds are Scots Pine, while the rest are Norway Spruce. Barring young stands, the carbon pools on Norway Spruce stands are considerably larger than those found on Scots Pine stands (Liski 2000).

3.2 Forest carbon pools

Forest biomass can be used in three ways to mitigate climate change (Soimakallio et al. 2009). It can either be a substitute for more energy intensive materials, it can sequester carbon from the atmosphere or it can conserve biogenic carbon within the biomass of forest and wood-based products. This in turn leads to three different mitigation strategies, which are substitution, sequestration and conservation management. In substitution management, the biomass is used to replace fossil fuel based alternatives; whereas with conservation and sequestration management, the amount of carbon stored in the biomass is either protected or increased, respectively. The effectiveness of the chosen mitigation strategy depends on the method and the relevant time-frame to mitigate climate change. The three strategies are typically optional to each other, in the sense that for example utilising the substitution strategy, the raw wood material cannot at the same time be conserved as living biomass. In certain situations however, conservation and sequestration strategies can overlap each other. This is the case for instance when the forests are protected.

Several specific strategies exist to increase the forest carbon pools and slow down the amount of CO_2 entering the atmosphere, each with varying risks, uncertainties and tradeoffs (Ryan et al. 2010). Avoiding deforestation and decreasing the harvests to keep the forests intact and to retain the forest carbon would be considered conservation strategies. Conservation has relatively low risk and a huge potential. Global deforestation releases some 1400-2000 TgC (~5138 – 7340 $TgCO_2$) to the atmosphere each year. To put it in to a perspective, deforestation releases hundred times more CO_2 to the atmosphere each year than the total annual Finnish CO_2 emissions.

The sequestration strategies involve afforestation and increasing the growth through forest management and silvicultural practices. In Finland afforestation and management practices are governed by the law. The Finnish Forest Act is to ensure economically, ecologically and socially sustainable and responsible use of Finnish forests (Ryan et al. 2010).

As opposed to conservation and sequestration strategies, substitution strategies help to mitigate climate change by utilizing harvested wood to offset fossil fuel emissions. The substitution benefits come from both using wood fuels to substitute for fossil fuels, and material substitution when products with lower associated greenhouse gas emissions are manufactured from wood and used. In the United States for example, the forests could potentially provide energy production to offset 190 TgC (~697 $TgCO_2$) of emissions each year. The substitution strategies are tricky as providing more energy wood or wood raw material for manufacturing of wood products would required intensifying forest management, which in turn could decrease the carbon pools in the forest, hence negating the first two mitigation options (Ryan et al. 2010).

Most studies support the notion that longer rotation lengths are better for the forest carbon pools. It is also one of the forest management actions that countries can apply, under the Article 3.4 of the Kyoto Protocol, to help reduce their greenhouse gas emissions. Changing the harvesting regime of a steady-state stand can turn into either a source or a sink for carbon, until it reaches a new steady-state with the new harvesting regime. Liski et al. (2001) simulated three different rotation lengths of 60, 90 and 120 years, for Scots Pine and Norway Spruce stands in Finland. Their results indicate that the longer rotation length would be better for the carbon budget on stands. Shortening the rotation from 90 years, closer to the culmination point of the mean annual increment (MAI), decreased the forest and product carbon pools for Scots Pine, while increased them for Norway Spruce. With the shorter rotation length, the carbon in the forest vegetation decreased, but the soil carbon increased, because of increased amount of harvest residue and litter from the trees. The total roundwood yield increased on both stands, but only the Norway Spruce wood product carbon pools increased. The younger stands yielded less sawlogs and more pulpwood and due to shorter lifespan of the pulpwood products, the emissions from harvesting, and the process energy involved in the manufacturing, the increased amount of pulpwood was not enough to compensate for the lost sawlogs on the Scots Pine stands, while on the Norway Spruce stands it was just enough. For these reasons they concluded that the longer rotation length is better for the overall carbon budget. The rotation length of 120 years showed to be clearly the better regime for the Scots Pine, while for the Norway Spruce stands, the conclusions were not so evident. For the forest owners however, the longer rotation lengths were not so attractive as they had a negative impact on their discounted net income (net present value, NPV).

Kaipainen et al. (2004) analyzed the carbon pools and managing rotation lengths in different European forests; Finnish, German and British spruce stands, and Spanish and German pine stands. They simulated increasing the rotation by 20 years from the recommended to study the effects of elongated rotation periods on the average carbon pools in the trees, soil and the wood products. Elongating the rotation increased the carbon pools in all the forests, however in some cases this also lead to a 1 – 6 % decrease in the harvesting possibilities. Despite this the overall carbon pools increased in all the cases.

Pingoud et al. (2010) studies the effects of different silvicultural regimes on the integrated climatic impacts of forestry and the use of wood-based products. Their findings suggest that the generic mitigation strategies are not necessarily mutually exclusive. Depending on the applied silvicultural regime, forest wood yields change and so do the possibilities of using wood. Because wood products store carbon and have substitution benefits in the form of avoided emissions, different silvicultural regimes can affect the potential to offset greenhouse gas emissions. The forest carbon pools are also affected by the regimes because as the growth of the forest changes, it has an impact on carbon sequestration and the size of the pools. Their results indicate that elongating the rotation periods could have positive impacts on both the carbon pools and the avoided emissions from substitution. They found that lengthening the rotation from the current recommended, and increasing the average basal area of the forest, lead to a higher production of sawlogs. This subsequently led to larger carbon pools and higher levels of avoided emissions as energy intensive materials were increasingly substituted by sawnwood. Their findings suggest that changing the current forest management practices in Finland could possibly lead to win-win scenarios where the forest and wood-product carbon pools, as well as the avoided emissions, are increased from the current levels.

Perez-Garcia et al. (2005) have similarly studied the effects of silvicultural regimes and the integrated climatic impacts, but they reached a somewhat different conclusion than Pingoud et al. (2010). Instead of increasing the rotation lengths and the basal area, more intensive silviculture with shorter rotations and more harvests showed the highest emission reductions. The somewhat contradictory findings are mostly due to the different biological properties of the forests studied, as well as the different geographical locations and the industry structures in the regions. The study concluded that increasing the use of wood is desirable, and leads to higher climate benefits than leaving forests in their natural state, but only as long as forests are managed in a sustainable way, the wood waste is taken care of and the by-products are used responsibly.

3.3 Forest product carbon pools

When wood is harvested, the carbon leaves the forest, captured within sawlogs and pulpwood. The carbon content of wood is approximately half of the dry weight of the wood, though the exact amount varies between the tree species. Carbon remains captured within the wood, until the product reaches the end of its lifecycle. The climatic benefits from the product carbon pools largely depend on the delayed re-emissions of biogenic carbon to the atmosphere. Buchanan and Levine (1999) assert that the carbon stored in wood products must be included in any study that addresses the complicated relationship between the forest industry and global carbon emissions. On average, paper and paper products decay within five years, whereas lumber used for housing can last for more than a hundred years (UNFCCC 2003). Pingoud et al. (2001) have estimated that in Finland the average lifespan of sawnwood product is approximately 40 years.

The length of a product lifecycle is an important factor, however as cellulose fibers can be reused up to 6 times, the amount of time the pulpwood products can store the carbon is multifold through recycling. After being no longer in use, the product may be recycled, incinerated or land-filled, which then releases some or all of the carbon back to the atmosphere. Because not everything is incinerated or recycled, the carbon in wood products can be found in two basic pools, in those products that are still in use, and the products which are decomposing at the landfills. The decay of wood products in landfills can be very slow, and some of the carbon in the wood waste may never return the atmosphere. Pingoud et al. (1996) have estimated that the wood product carbon pool in Finnish landfills is twice as large and increasing, as the carbon pool of wood products in use. Unfortunately anaerobic decomposition also produces methane (CH_4), a greenhouse gas 25 times more potent than CO_2, which reduces the carbon storing benefits of landfills (Ryan et al. 2010).

Laturi et al. (2008) estimate that the amount of carbon stored in wood products in Finland is about 26.6 TgC (~97 $TgCO_2$), including only the sawnwood products and wood-based panels. They showed that the forest product carbon pools have grown annually by about 0.7 TgC (~2.7 $TgCO_2$) between the years 2000 and 2004, at the time offsetting some 3 % of all greenhouse gas emissions in Finland. Furthermore, the carbon pools have vastly increased from the earlier decades, and they predict the trend will continue in the future as well. Even in their most pessimistic future scenario, the carbon reservoirs would increase by approximately 50 % from their 2004 levels in the next 40 years. They estimate that depending on the consumption, by 2050 the forest product carbon pools could be in the range of 39.6 – 64.4 TgC (~145.3 – 236.6 $TgCO_2$). These estimates might even be in the lower range, as they do not include pulpwood products or the carbon in wood at landfills. The amount of carbon at landfills might be especially substantial, as noted by Pingoud et al. (1996), as they estimated that the amount of carbon at landfills might be as much as twice the amount of carbon in wood products still in use. Because most of the wood products produced in Finland are exported, some two-thirds of the carbon pools associated with Finnish forest products can be found abroad.

In the United States the additions of carbon to the forest product carbon pools have been larger than the decomposition losses in the pools. For instance in 2007 the carbon pools increased by an estimated 30 TgC (~110 $TgCO_2$), offsetting some 1.7 % of all fossil fuel emissions in the United States. Ryan et al. (2010) conclude that if the same net amount of wood products going in to the landfills was used as wood energy instead, it could potentially offset about 1.2 % of the total fossil fuel emissions in the United States. About two-thirds of the net carbon additions are in to the landfill pools, however the carbon pools of the products is increasing as well, namely through construction of buildings. In total the forest product carbon pool of single- and multifamily homes was estimated 700 TgC (~2569 $TgCO_2$) in 2001. Skog and Nicholson (1998) have estimated that the total size of the forest product carbon pool in the United States is around 2700 TgC (~9900 $TgCO_2$).

Buchanan and Levine (1999) suggest that because of the finite lifetime of wood products, the wood product carbon pools cannot be used to offset the emissions on the long-term. They base this on the fact that the total carbon pools would remain at a constant level after reaching a steady-state around 40 years, corresponding with the average lifetime of products, while the cumulative emissions from manufacturing would still continue to increase. At the rate the carbon emissions would be equal to the wood product carbon pools after 150 years. The notion is the same as reach by Schlamadinger and Marland (1996). However, when also taking in to account the avoided emissions from wood use, wood is a good option and can help to decrease and avoid carbon emissions. They point out that sustainable forest management is one key requirement for climate change mitigation strategies that utilize forest resources.

4 GREENHOUSE GAS EMISSIONS AND SUBSTITUTION BENEFITS

4.1 Lifecycle assessment

Lifecycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's, service's or process' life from cradle-to-grave (EPA 2006). It enables the estimation of the cumulative environmental impacts that result from all the stages of the lifecycle (Figure 7).

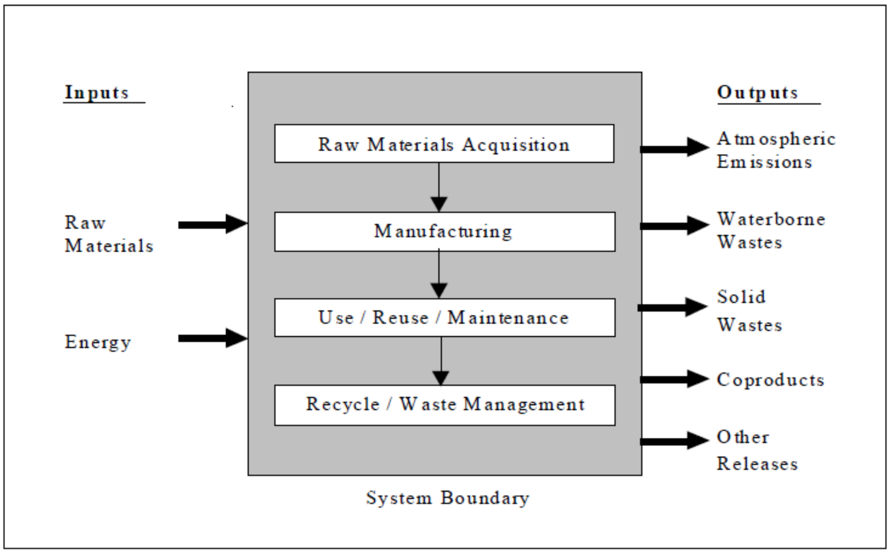

Figure 7. Lifecycle stages in the LCA (EPA 2006).

The purpose of a LCA is to assess the environmental aspects and potential impacts by compiling an inventory of all relevant energy and material inputs and releases, evaluating their potential environmental impacts, and interpreting the results in order to help decision-makers make more informed decisions (EPA 2006).

Lifecycle assessment is part of the International Organization for Standardization (ISO) environmental management standards ISO 14040 and ISO 14044 (ISO 2011). According to the standards, LCA is carried out in four phases (Figure 8). The process is systematic and phased, consisting of interdependent components in the sense that the results from one category will affect the others. A lifecycle assessment starts with the goal and scope setting. The purpose of the goal and scope setting phase is to set out the context of the study and explain how and to whom the results are to be communicated to. The inventory analysis (LCI) phase creates an inventory of all the inbound and outbound flows of materials and energy in the system. The impact assessment (LCIA) phase evaluates the potential human and ecological effects that result from the inbound and outbound flows, identified in the inventory analysis. The purpose of the final phase, interpretation, is just that. It evaluates the results from the inventory and impact categories, and its' purpose is to identify and signify issues based on these results, as well as evaluate the study as a whole and point out its' limitations, recommendations and conclusions.

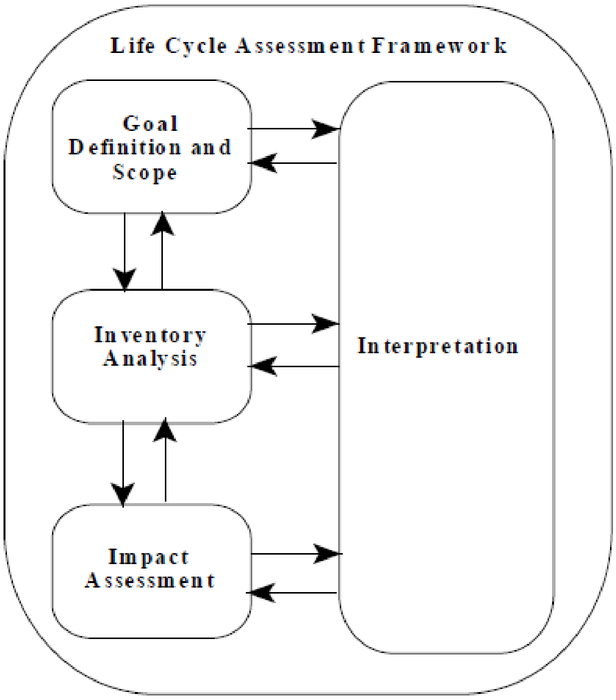

Figure 8. Phases of an LCA (EPA 2006).

4.2 Carbon footprint

A carbon footprint is the measure of greenhouse gas emissions associated with an activity, group of activities or a product. In principle the carbon footprint is the same as climate change impact category of a lifecycle assessment (Eriksson et al. 2009). The carbon footprints and the LCA of wood-based products have been extensively studied in recent years by both the industry and the scientific community. No unified methodology to assess the product carbon footprint exists as of yet. Several methodologies have been proposed or are currently under development, one of which is the Confederation of European Paper Industries' (CEPI) Carbon Footprint framework (Figure 9) launched in 2007, proposed for accounting the carbon footprint of forest and forest products (CEPI 2007). The so called “ten toes” represent the different ten elements of a carbon footprint for paper and paperboard products. This includes carbon sequestration in forests (toe 1), carbon stored in forest products (toe 2), greenhouse gas emissions from forest product manufacturing facilities, production of raw material and purchased electricity, steam, heat and water (toes 3-6), transport related greenhouse gas emissions (toe 7), emissions associated with the product use (toe 8), emissions associated with the product’s end-of-life (toe 9) and the avoided emissions and offset (toe 10).

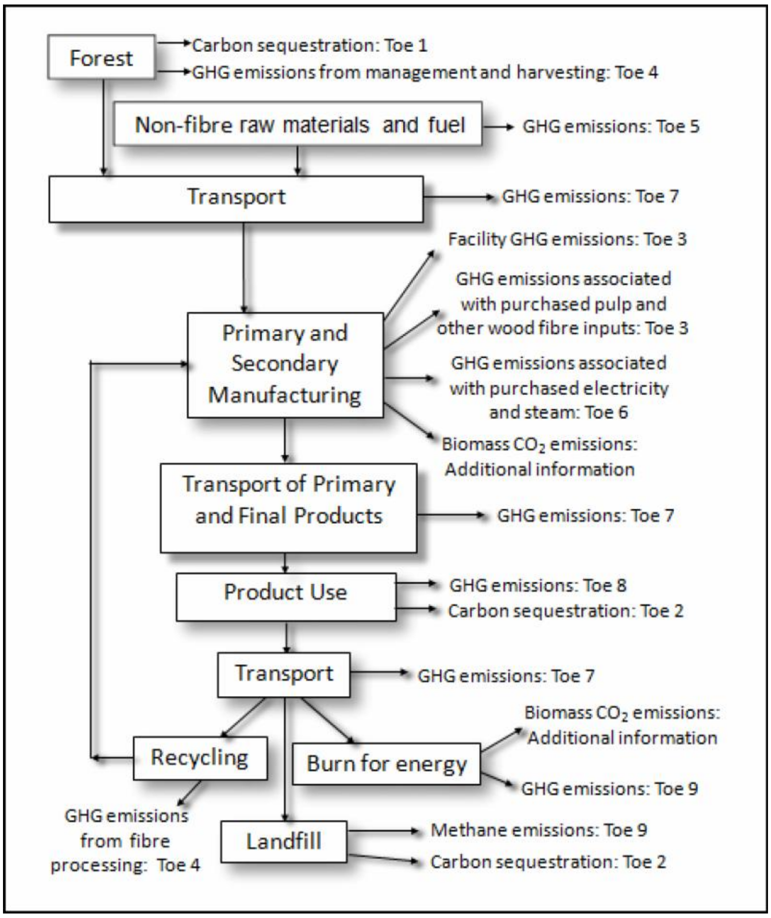

Figure 9. CEPI Carbon Footprint framework (CEPI 2007).

While in principle the same, the methodologies for calculating the carbon footprints differ in, for instance, how the biogenic carbon in the growing forest stock is accounted for (toe 1 in the CEPI framework) or rather if it is accounted for at all. CEPI argues that because of sustainable forest management, that is due to industry use of wood, which ensures the re-growth of the forests after harvesting, the inclusion of carbon sequestration in the forest to the forest product carbon footprint is necessary. The British Standard Institute (BSI) Publicly Available Standard (PAS) “Assessing the life cycle greenhouse gas emissions of goods and services” (BSI 2008) discusses the inclusion of biogenic carbon, but states that the biogenic carbon should be excluded from the carbon footprint and only the carbon stored in products, and the impact of land use changes can be included in the footprint . As stressed by Eriksson et al. (2009), until there is a detailed methodology and standard for the calculation of the carbon footprint, the differences in the accounting methods make it critical to acknowledge and describe in detail the conditions and methods used in the LCA studies.

The International Organization for Standardization (ISO) has begun working on a new uniform standard for the quantification and communication of greenhouse gas emissions associated with goods and services. The standard for “Carbon Footprints of Products” ISO 14067 (ISO 2011) is largely built on the existing ISO standards for life cycle assessments and environmental labels and declarations. The standard is planned for release in 2012. In comparison to the existing lifecycle assessment standards, the new standard contains further improvements to the quantification of greenhouse gas emissions. As of May 2011, it is still at the committee stage for further comments and voting. The inclusion of biogenic carbon in the forest is at the time of writing this uncertain, however the inclusion has been discussed within the working group of the ISO 14067.

4.3 Avoided emissions

Substitution strategies help mitigate climate change by utilizing harvested wood to offset fossil fuel emissions, by replacing fossil fuels and more energy intensive materials with wood (Schlamadinger and Marland 1996). Because of the finite lifecycle of wood, in the long run, the amount of carbon stored in the forest and in forest products reaches an equilibrium, and a continuing mitigation of carbon emissions depends on the extent to which fossil fuel use is displaced by the use of wood energy and wood products.

Schlamadinger and Marland (1996) present the idea of displacement factors, which describe the direct and indirect energy substitution of wood use. The difference is that direct energy substitution comes from the amount of carbon emissions that are avoided when wood energy is used instead of fossil fuels, whereas indirect energy substitution is the amount of carbon emissions avoided by replacing energy intensive products with wood products of the same function. Thus the efficiency and the substitution benefits depend purely on the reference system the wood is used to replace.

Wood in generally is seen as a good option in reducing the amount of greenhouse gas emissions released to the atmosphere. Reid et al. (2004) for example affirm that on average using one cubic meter of wood to substitute for other construction materials (concrete, blocks and bricks), results in 0.75 – 1 tCO_2 emission reduction. Sathre and O'Connor (2008) have more extensively reviewed 48 studies on the climatic impacts of wood use in construction. They found that all the studies reviewed suggested that the production of wood-based materials and products resulted in less greenhouse gas emissions than their alternatives. According to the reviewed articles, the single most significant source of variability in the greenhouse gas emissions appeared to come from the end-of-life management. Also, in several studies the use phase of the building was a more significant source of greenhouse gasses, than the actual construction or disposal phase. They concluded that to minimize the climatic impacts, the whole lifecycle of the materials should be considered, not just the building phase. A meta-analysis on the displacement factors used for sawnwood was also carried out on a basis of 20 scientific articles. They found that the displacement factors used ranged from a minimum of -2.2 to a maximum of 15.0, with an average low of 0.7, to an average middle of 2.0, to an average high of 4.4. They concluded that the average middle estimate of 2 could be viewed as reasonable middle estimate for an end-product sawnwood displacement factor. This means that for each ton of carbon in wood product used to substitute for an alternative material, a greenhouse gas emission reduction of 2 tC is achieved. They further note that in comparison, the displacement factors suggested for energy wood typically range between 0.5 – 1.

The main opportunities for using wood to mitigate climate change come from using a greater amount of wood to substitute for more energy intensive materials, extending the lifespan of wood products and increasing the recycling. Hekkert et al. (2000a) have estimated by examining different scenarios, the potential to reduce the packaging greenhouse gas emissions. Improving the material design alone, namely by designing lighter packages with less material, showed a 9 % reduction in the overall CO_2 emissions, while material substitution showed a 10 % reduction. From the emission reduction point-of-view, the most promising improvement appeared to be substituting single use packages with reusable packaging, which showed a 32 % reduction in the CO_2 emissions. The total technical potential of CO_2 emission reductions was estimated 51 %. The approaches differ from each other in how complex they would be to implement. Low complexity measures, such as material redesign, would only involve the use of less, lighter and thinner materials and for which only the measures from the packaging manufacturers would be necessary. Medium complexity measures, such as increased material substitution, would also involve the material production sector, as well as the packaging manufacturers themselves. The measure with the highest complexity and incidentally the hardest to implement, would require changes in all stages of the packaging material lifecycle.

Some legislative and regulatory constraints for substitution exist as well (Reid et al. 2004). For example in the food packaging industry, which globally represents about half of the fibre-based packaging consumption (Finnish Forest Industries 2011), strict hygiene and preservation requirements restrict and limit the potential to use fibre-based materials. Incidentally packaging materials are seldom used singly but as a combination of many different materials. For example aseptic liquid packaging systems are made from liquid packaging board, which combines paperboard with low-density polyethylene (LDPE) coating and aluminium foil.

4.4 Comparative packaging lifecycle assessment studies

The Swedish Environmental Research Institute (IVL) has studied the carbon footprint of carton (Eriksson et al. 2010) and the carbon footprints of all basic products of the Billerud group, as well as conducted case studies on two specific fibre products (Eriksson et al. 2009). The methodology used by the IVL studies followed the CEPI Carbon Footprint framework, which also included separately calculating the biogenic CO_2 net sequestration in managed forests. Their comparative study showed that both plastic bags and sacks contributed more to the greenhouse gas emissions than their paper alternatives, when applying the European average end-of-life management treatments. The associated emissions for paper sacks were less than two-thirds of the emissions associated with the plastic alternative, and the paper bags fared even better (Figure 10). They noted that the single most significant source of greenhouse gas emissions with the paper bags and sacks was methane emissions at the landfilling stage. The 100 year time horizon used was slightly unfavourable for wood, as during this time only 3 % of the plastics were assumed to decay, whereas the wood decay at this point was assumed to be 70 %. With less landfilling the results would look more favourable for wood. If biogenic CO_2 sequestration was included in the footprint as well, the results would look even more favourable. Eriksson et al. (2010) also calculated the average carbon footprint for carton in Europe as 1127 kgCO_2eq cradle-to-grave. Direct comparison to alternative materials is not possible however, as a result of the vastly different mass ratios of end-products with the same functional purpose (Pilz et al. 2010). The results also proved very sensitive to whether or not the biogenic carbon sequestration is included or not, as IVL calculated the amount of biogenic carbon sequestration to be 730 kgCO_2eq for a ton of carton. Compared to the cradle-to-grave emissions of 1127 kg CO_2eq, the inclusion of biogenic carbon would offset two-thirds of the total greenhouse gas emissions.

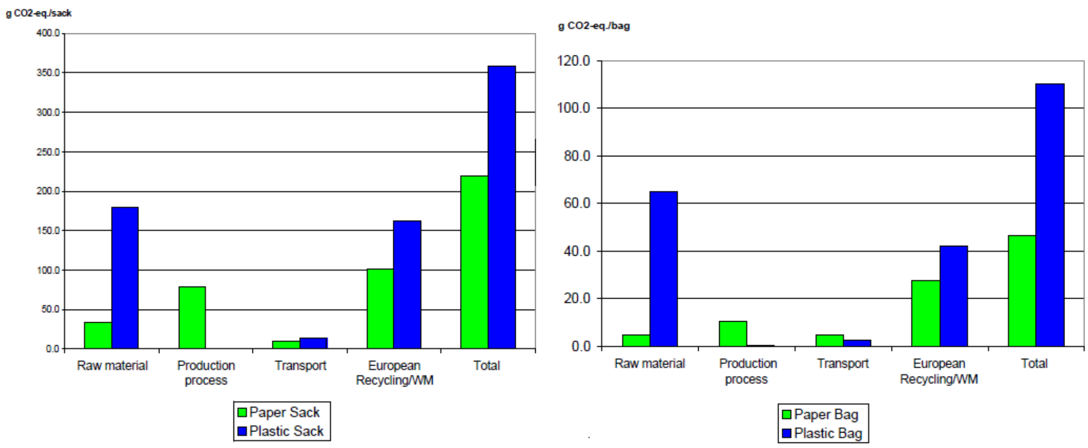

Figure 10. GHG emissions from paper and plastic bags and sacks (Erikkson et al. 2009).

In a lifecycle assessment (LCA) study by the German Institute for Energy and Environmental Research (IFEU), Detzel et al. (2008) compared the carbon footprints of milk and juice containers in the Spanish markets. The study examined the packaging systems most commonly used in the Spanish market, beverage cartons and HDPE and PET bottles, for the two most important beverage varieties in Spain, UHT (ultra-heat treatment) milk and juice. They show that in all the cases, the greenhouse gas emissions associated with the products were dominated by the greenhouse gas emissions of the production phase, and that the PET bottles produced considerable higher greenhouse gas emissions, than the beverage cartons. The end-of-life management options considered were energy recovery, landfilling and recycling, by applying the average end-of-life management treatments in Spain. For the small portion packs, the PET bottles showed 2 – 3 times higher emissions, than the beverage cartons. In a cumulative comparison the greenhouse gas emissions associated with milk and juice family packs, the 1 litre PET milk bottle showed approximately 80 % higher associated emissions than the beverage carton alternative. For 1 litre PET juice bottle, the emissions associated were approximately 120 % higher than with the beverage carton. In comparison with the HDPE bottles, the results depended heavily on the end-of-life management, but still showed favourable to the beverage carton. Again the end-of-life management was found to have a high importance in the favourability of the materials, as the variation was mostly due to the methane emissions associated with landfilling. While plastic bottle waste is practically inert in landfills, the beverage carton is a potential source for greenhouse gas emissions through the methane generation. They note that in countries where landfilling of untreated packaging waste has been banned, the beverage cartons would show even more favourable lifecycle carbon footprints. In a similar IFEU study, Wellenreuther et al. (2008) did a more comprehensive study with similar products in the Spanish markets, as Detzel et al. (2008), reaching supporting conclusions. They found that the beverage cartons showed smaller climatic impacts than the PET bottles in almost all the impact and inventory categories, and that the sensitivity analysis only changed the magnitude of the results. The net results for the HDPE bottles were lower than for the PET bottle, but in comparison to the beverage cartons, they still fared worse.

In another IVL LCA study on the packaging systems for liquid foods, Jelse et al. (2009) analysed the packaging systems of four different products groups, dairy, juice and two portion packaged beverages in the Nordic markets; Finland, Sweden, Denmark and Norway. They found that on all the four markets, the dairy and juice carton packages had significantly lower contributions to the global warming potential (GWP) than the PET or HDPE packages. With the larger of the two portion packaging systems studied, the greenhouse gas emissions of the disposable glass packaging were found to be the highest. With the smaller portion packaging system, the HDPE package had higher associated greenhouse gas emissions than the beverage carton, again on all markets. The results from the IVL study were in line with the finding by IFEU on the Spanish beverage markets.

In a lifecycle assessment of beverage cups, Häkkinen and Vares (2009) found that when comparing PET and carton based cold drink cups, the carton based cups had a considerably lower global warming potential than the PET cups. The consumption of fossil fuels for the production of 100000 PET based cups was estimated to be five times higher, than for carton cups, and the CO_2 emissions for paper cups were only a fifth of the PET cups'. The end-of-life management was again noted having a significant impact on the results.

Zabaniotou and Kassidi (2003) compared polystyrene (PS) and recycled paper egg packaging systems in Greece. Because of the actual waste management in Greece, it was assumed that both packages would be disposed in landfills and no other options were considered. As noted before, the end-of-life management is of high importance in how the materials fare compared to each other. Recycling is generally considered to be desirable and necessary, and waste management policy in many countries considers (as well as the European Union waste hierarchy) the reuse and recycling to be preferable and superior to energy recovery or landfilling. The results show that the fibre-based packaging had lower greenhouse gas emissions and global warming potential, and it consumed less energy in the production, than polystyrene packaging. In all but two of the LCA impact categories, the recycled paper egg package had a lower impact score and the results clearly show that the fibre alternative had a lower overall impact on the environment.

Grönman (2009) compared carton-based fibre-molds and expanded polystyrene (EPS) systems in a secondary packaging application for foodstuff. The results show that if the fibre-molds are recycled, the fibre based system is clearly better than the EPS system, showing approximately 43 – 56 % lower overall emissions. End-of-life management scenarios were also considered, which showed that if the waste was landfilled or incinerated with energy recovery instead of recycled, the EPS system would be better. It was noted however, that in the case of Finland, majority of the waste would be recycled.

Singh et al. (2006) compared re-usable plastic containers (RPC) and display-ready corrugated containers (DRC) used for packaging fresh fruits and vegetables in the in the North American market. Their results show that for the 10 different product items reviewed, in 18 out of 20 cases, the RPC generated on average 29% less greenhouse gas emissions than the DRC. Their results indicated that for these applications, re-use with closed-loop recycling was a more efficient way to reduce greenhouse gas emissions than using DRCs. The problem with the use of RPCs is however that they are 5 – 10 times more expensive than DRCs and require a well-organized large logistical chains to off-set the costs (Twede et al. 2005). Two notable examples of such logistical supply chains are the US automobile assembly industry, and the fresh-produce industry supplying some of the US grocery store chains.

In a European Federation of Corrugated Board Manufacturers study, Vogtländer (2004) compared similar fruit packaging systems as Singh et al. (2006) but in the European market. The study included the costs and the eco-costs for the whole system including packaging, transport, storage, handling, return flows and cleaning of the RPCs. The problem was approached from an eco-cost point of view, which helps to allocate the direct and the indirect environmental burdens in lifecycle analysis, that come associated with the complex nature of the transport service systems. The study found that the corrugated board system was better in all cases, however on short distances of 500 km and less, the differences were negligible. The costs for rigid container and corrugated board systems were the same for the distance of 500 km, whereas the foldable container system was found to be more expensive.

The change from a DRC system to a RPC system would be a high complexity measure and thus hard to implement, as changes in all the stages of the packaging material lifecycle would be necessary. Hekkert et al. (2000b) have extensively analysed the different road transport packaging related environmental impacts in Western Europe, including the corrugated boxes and reusable plastic containers. They estimate that by substituting corrugated boxes with reusable plastic crates, some 12 % emission reductions could be achieved. They assumed a transport distance of 200 km to be the realistic upper limit and noted that the results are very sensitive to this. In fact if the transport distance doubled, the reusable plastic crate would no longer be an improvement option. Depending on the density of the population, the transport distances vary between different European regions. The pooling system matters as well, as depending whether plastic crates would be returned to the pooler or the distributor, the environmental impacts could show more favourable to the reusable plastic crates, as the same truck could be used for the returns as well. The calculations for the eco-cost are highly sensitive to the material prices fluctuations. Based on the price data of the time, for instance a price drop of 50 % for the corrugated board box, would increase the eco-cost of this mitigation option from 15 e/tCO_2eq to 100 e/tCO_2eq saved.

4.4.1 Summary of the findings

Based on the literary analysis, there seems to be clear indications that fibre-based materials in primary and secondary packaging use have positive environmental impacts, compared to alternative materials. In fact, the emissions of non-wood materials showed in many cases over twice the emissions of the fibre-based alternatives. In addition to the reviewed studies, this view is supported by for example Larvio (2008) and Pasqualino et al. (2011), in their beverage packaging system studies in the Finnish and the Spanish markets, Banar and Cokaygil (2009), in their cheese packaging study, and Singh and Krasowski (2010), in their comparative lifecycle assessment of selected fruit packaging systems.

In the case of tertiary packaging, the issue is more complex. Moving away from primary and secondary packaging opens the window for more flexible options and logistical solutions concerning packaging, as the distance between the product and the consumer increases. Especially in the case of corrugated board and reusable plastic container systems, there seems to be a high amount of uncertainty surrounding the question of which system is better. Three issues seem to be of high importance; the transport distances, the energy used in manufacturing of materials and the end-of-life management. Most of the energy consumed by the forest industry in Finland is self-generated with renewable wood fuels. In Finland corrugated board used by the industry accounts for approximately 60 % of all fibre-based packaging material consumption. The recovery rate for corrugated board in Finland is extremely high, as 90.8 % of the corrugated board waste is recycled and 7.7 % incinerated with energy recovery. The transport distances are also of high importance, as the RPCs have to be pooled back-and-forth. The pooling in itself matters as well. In Finland large-scale closed-pool systems, where the ownership of the containers is maintained by the pooler, as examined by Singh et al. (2006), have not been studied or do not exist. For these reasons, there is a high amount of uncertainty how applicable the results would be to Finland.

The boundaries set by the LCA studies can have a major impact on the results. In general, all LCA studies are quite sensitive to the energy systems used, as well as the end-of-life management scenarios. For instance Mourad et al. (2008) point out how different recycling rates for aseptic milk cartons change the amount of associated greenhouse gas emissions. Simply by recycling the carton content and increasing the recycling rate from 2 % to 22 %, the global warming potential decreased by 14 %, while a 70 % recycling rate showed the GWP decrease by 56 %, from the baseline of no recycling. Noteworthy is also that many of the factors affecting the potential climatic impact of packaging, are intervened in such ways that for example optimizing the material use not only has a positive impact on the production phase, but also the lighter weight of the new design has the potential to improve the fuel economy of all associated land transports later in the transportation phase (IPCC 2001). The inclusion of biogenic carbon sequestration in managed forests would also show very beneficial for the wood products, as it would in many cases offset a large portion of the total wood product carbon footprint.

5 METHODOLOGY AND DATA

5.1 The basic approach

In short, the basic idea is to examine the climatic impacts of fibre-based packaging material production and consumption at its current level through different forest management and end-use scenarios. The baseline forest and forest product carbon pools and the avoided emissions from wood use are compared (1) to carbon pools, and (2) to avoided emissions under alternative forest management regimes and end-use scenarios. Different forest management regimes are generated by optimizations and stand simulations. Under the alternative scenarios the wood yields change, as the pulpwood supply decreases. A decrease in the price of pulpwood reflects the decreased demand for - and consequently the supply of - fibre-based packaging materials. Therefore, the baseline corresponds with the highest level of fibre-based packaging material supply in all scenarios. The comparison of the climatic indicators between scenarios give an insight into the sustainability of fibre-based packaging materials, and the climatic impacts of decreased material supply and substitution under the alternative scenarios.

The scenarios considered in the study are the following:

I. **Baseline:** Economically optimal forest management (maximized bareland value)

II. **Reduced pulpwood demand (RPD):** Forest management and wood yields change, due to the drop in pulpwood price which changes the optimal forest management. Paper, energy and packaging supply stay proportionally fixed.

III. **End-use scenarios:**

   a. **Sawlog:** The reduced demand for packaging materials (reflected by the pulpwood price) leads to an increased sawlog production. No change for paper or energy wood. Forest management regime same as in RPD.

   b. **Energy wood (Energy):** The demand shifts from packaging to energy use. No change for paper or sawlogs. Forest management regime same as in baseline.

IV. **Tapio:** Forest management by silvicultural guidelines developed by the Forestry Development Centre Tapio. Product mix proportionally fixed to the baseline.

The economically optimal forest management was chosen in order to attain a reasonable baseline, from which to generate sensible alternative scenarios, in which the pulpwood supply decreases. In the first of the two end-use scenarios the demand shifts from pulpwood to sawlog production, which is interesting from both the industry and forest owner point-of-view. The energy scenario is especially interesting policywise, as pulpwood is already in some cases used for energy purposes, instead of pulpwood products. The guidelines developed by the Forestry Development Centre Tapio are also included, as they are the current basis of forestry practices in Finland.

5.2 Steady-state framework

The methodology of the study is based on a stand-level steady-state analysis (Figure 11), where the steady-state forms a fully regulated forest, sustainably managed in a long-term equilibrium. The growth of the forest equals the removals, and the influx of wood raw material for wood based products, equals the material decay, similarly to Pingoud et al. (2010). The annual wood yield is the mean annual increment (MAI), which is the cumulative wood yield of the stand, divided by stand rotation length (1).

$$MAI = \frac{q(t)}{t} \quad (1)$$

where q(t) is the cumulative yield (m^3) at the time of the final harvest t (years) .

The steady-state forest represents a normal forest, composed of even-aged, fully-stocked stands, where one age class can be harvested each year, so that after each specific rotation period, the stands harvested first, would be ready to be harvested again. The carbon sequestration rates, as well as the raw material flows and allocations, differ depending on the forest management scenario, leading to varying carbon stock levels and avoided emissions from wood use. The idea is to compare these steady-states to one another, to see what kind of climatic impacts each of them has.

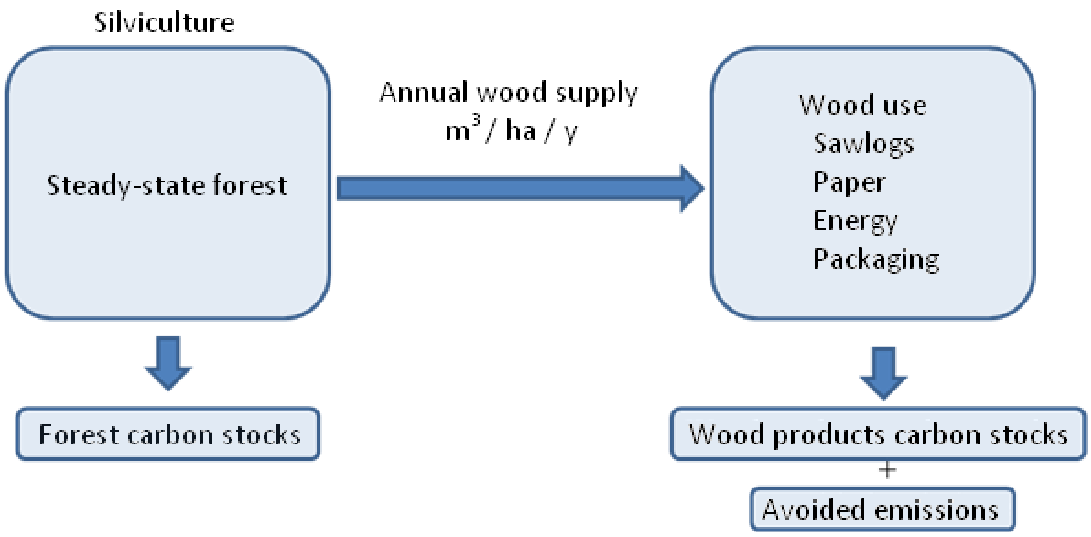

Figure 11. Steady-state framework.

5.3 Forest stand data

The forest stand data were obtained from two different datasets at an earlier stage of the project. The datasets came from the Finnish Forest Research Institute Metla. The first dataset consisted of Norway Spruce and Scots Pine stands, located in Päijät-Häme. The second stand data was collected from a Metla TINKA dataset, and included stands in Southern and Central Finland, established by the Finnish Forest Research Institute. The stands were established in 1985 – 1986, and measured during the National Forest Inventory (NFI). Of the final stands chosen for the study, 8 were Scots Pine and 6 were Norway Spruce (Table 3).

Table 3. Forest stands data at the beginning of simulations.

Stand	Species	Site type	Location	Age	N	BA	Hg	Dg	Hdom
1	Scots Pine	VT	Etelä-Pohjanmaa	18	1371	8,0	6,7	10,9	7,8
2	Scots Pine	VT	Keski-Suomi	20	2076	11,4	7,7	11,1	9,1
3	Scots Pine	VT	Pohjois-Karjala	19	1861	7,2	6,6	9,4	8,5
4	Scots Pine	VT	Päijät-Häme	11	2390	4,3	4,7	6,3	7,1
5	Scots Pine	VT	Etelä-Savo	15	2375	24,1	9,6	12,0	10,4
			Average	***17***	***2015***	***11***	***7***	***10***	***9***
6	Scots Pine	MT	Itä-Savo	23	1876	14,1	8,8	12,4	9,7
7	Scots Pine	MT	Päijät-Häme	11	2110	6,7	5,9	8,0	8,6
8	Scots Pine	MT	Päijät-Häme	12	3600	14,9	6,6	9,0	10,5
			Average	***15***	***2529***	***12***	***7***	***10***	***10***
9	Norway Spruce	MT	Keski-Suomi	22	1575	4,8	5,5	6,9	7,0
10	Norway Spruce	MT	Kainuu	17	2076	3,2	3,3	5,3	3,9
11	Norway Spruce	MT	Päijät-Häme	22	2200	2,1	3,8	5,0	5,6
			Average	***20***	***1950***	***3***	***4***	***6***	***5***
12	Norway Spruce	OMT	Keski-Suomi	21	1498	5,0	6,5	7,9	8,4
13	Norway Spruce	OMT	Päijät-Häme	22	2000	1,9	3,8	5,0	5,4
14	Norway Spruce	OMT	Päijät-Häme	21	2500	3,4	4,3	5,7	6,5
			Average	***21***	***1999***	***3***	***5***	***6***	***7***

All the stands were measured in the field before their first thinning. The biological age of the stands varied between 11 – 23 years at the time of the measurements. The number of trees per hectare varied between 1371 – 3600 for Scots Pine and 1575 – 2500 for Norway Spruce. At this point they had reached a stable state, so that they were not directly threatened by the competing vegetation. The variation in the number of trees at the beginning of the simulations gives diversity to the results, and covers a large portion of actual growth situations in Finnish forests. Selecting young stands also gave more freedom in optimization and allowed more flexibility in the analysis that followed.

The stands consisted of three different site types; MT (Myrtillus), OMT (Oxalis Myrtillus) and VT (Vaccinium). The three represent the most common site types in Southern Finland, so including forest stands from these sites was logical. Myrtillus is most common site type, representing approximately 45 % of forest surface area in Southern Finland, while Oxalis Myrtillus covers some 29 % and Vaccinium nearly 20 % (Hotanen et al. 2008, p. 99 – 135). On the Scots Pine sites, the regeneration methods were planting, seedling and natural generation. On the Norway spruce sites, the only regeneration method was planting. The history of the stands, except for their respective regeneration methods, is unknown.

5.4 Stand Management Assistant and MOTTI simulations

Stand management for the plots was first optimized with the help of Stand Management Assistant (SMA) software, which is a software for analyzing silvicultural and economic options in stand management. The user can determine the optimal regimes for the present conditions, and view the results of the optimizations. The software includes different treatments such as thinnings and planting density (Valsta et al. 1996). Economically optimal forest management was chosen as the baseline for the stand optimization. This allowed generating an alternative forest management regime, by decreasing the price of pulpwood, while other variables were held constant. The decreased price of pulpwood is thought to reflect the decreased demand for fibre-based packaging materials. Therefore SMA was used in order to first find the sensible forest management practices, that would lead to such effects on wood production and supply, that were pursued, and to see what kind of simulations would have to be carried out later.

After optimization, each stands was simulated in MOTTI, a stand-level analysis tool, developed by the Finnish Forest Research Institute (Metla), with three different forest management regimes applied for each stand. MOTTI includes the newest empirical growth models from Finland, and thus is a suitable tool for assessing the stand-level effects of different forest management practices on the stand development and growth. It includes cumulative wood yields over the stand rotation, as well as the tree biomass (stem, branches, foliage and roots), which is essential in order to calculate the carbon sequestration in the forest. The simulator is suitable for analyzing Scots Pine, Birch and Norway Spruce. The current version of MOTTI is not suitable for uneven-aged forest management, so it was not considered. The forest biomass and the wood yields used for all the calculations were obtained through the MOTTI simulations.

In total two different optimizations and three simulations were carried out for each stand. The baseline maximizes the bareland value of the forest. The second forest management regime was generated by changing the price of pulpwood, which changes the optimal forest management. This was done in order to simulate the effects of reduced fibre-based packaging demand, which would negatively affect the price of pulpwood. This leads to varying thinning and harvesting frequencies, and rotation lengths, due to the changes in the optimal forest management behaviour under the new pulpwood price. The silvicultural guidelines developed by the Forestry Development Centre Tapio were also considered, and simulations following the guidelines were carried out. The guidelines are interesting because they are descriptive of the current management practices in Finland. The simulations and optimizations were carried out at an earlier stage of the project during summer 2010.

5.4.1 Price data

In order to determine the economically optimal forest management, the bareland value of the forest had to be calculated. For this cost and price data were needed. Trend prices for roundwood were derived from the average roundwood prices in Finland between 1995 and 2009 (Table 4).

Table 4. Roundwood prices (€/m^3) in Finland between 1995 and 2009 and trend prices for 2010.

	Sawlogs		Pulpwood	
Year	Pine	Spruce	Pine	Spruce
1995	47,68	38,13	17,96	21,16
1996	46,75	38,42	18,41	23,09
1997	50,15	41,23	17,90	24,34
1998	51,04	42,50	17,60	24,82
1999	50,11	44,11	16,36	24,40
2000	50,53	46,73	15,79	24,05
2001	47,80	44,65	14,54	22,82
2002	47,88	45,03	14,60	22,91
2003	47,19	44,97	13,82	21,67
2004	46,28	45,52	12,60	20,68
2005	44,34	46,52	12,56	20,83
2006	48,00	49,53	13,03	21,46
2007	62,95	64,50	15,65	23,32
2008	53,17	53,05	15,76	21,20
2009	40,84	41,30	12,87	17,46
2010	*49,44*	*53,16*	*12,45*	*20,16*

The harvesting costs were obtained from Metsäteho (2010) and they represent the average harvesting costs of 2010. The costs are presented in the following Table 5.

Table 5. Harvesting costs.

€/m^3	Harvesting costs
Pine sawlogs	7,11
Spruce sawlogs	6,63
Pine pulpwood	12,48
Spruce pulpwood	12,34

For Scots Pine the roadside wood price was 56.5 e/m^3 for sawlog, and 25 e/m^3 for pulpwood and for Norway Spruce 59.8 e/m^3 for sawlog and 32.5 e/m^3 for pulpwood. In the alternative (RPD) price scenario, the sawlog price remains unchanged, but the pulpwood price decreases by 10 €. The average roadside and the scenario prices are presented in Table 6.

Table 6. Roadside wood prices (€/m^3) (= stumpage price + harvesting).

	Sawlogs		Pulpwood	
	Pine	Spruce	Pine	Spruce
2010	56,55	59,79	24,93	32,50
Baseline	56,55	59,79	24,93	32,50
Tapio	56,55	59,79	24,93	32,50
RPD	56,55	59,79	*14,93*	*22,50*

The forest management costs were obtained from Metla (MetINFO 2010) and they're presented in the following Table 7.

Table 7. Forest management costs.

Forest management	€/ha
Planting	642,2
Seeding	200,3
Sapling management	381,1
Harrowing	164,2
Mounding	301,6

The interest rate used in the calculations was 3 %. This is about an average used in forest and other types of low-risk investment calculations, and it represents the risk-free interest rate obtainable by the investor through government bonds (Knüpfer and Puttonen 2004, Holopainen and Viitanen 2009). Using a higher interest rate would suggest higher risk involved, and in the simulations, it would shorten the rotation lengths as the higher interest rate decreases the value of all future cash flows.

5.5 Wood supply in baseline and the alternative scenarios

The cumulative wood yields over the stand rotations obtained from MOTTI, were divided by their rotation lengths, to obtain the annual wood yields. The average wood yields are calculated for species with the same site type, Vaccinium (VT) and Myrtillus (MT) for Scots Pine, and Myrtillus (MT) and Oxalis Myrtillus (OMT) for Norway Spruce. The effects of the three different silvicultural regimes, as well as the mean annual yields for each regime, are presented in the following Table 8.

Table 8. Average stand characteristics at the time of the final harvest. MAIt is the total annual yield, MAIsl is the annual sawlog yield and MAIpw is the annual pulpwood yield.

Species	Site	Regime	Age	N	BA	Dg	Hdom	V	MAIt	MAIsl	MAIpw
Scots pine	VT	Baseline	70	576	23,8	24,5	19,1	203	4,94	2,21	2,73
		RPD	74	516	23,4	25,5	19,6	204	4,85	2,37	2,48
		Tapio	68	446	21,7	25,6	19,0	187	4,50	2,23	2,27
Scots pine	MT	Baseline	63	419	25,7	29,3	23,9	260	7,44	4,00	3,44
		RPD	65	385	25,8	30,2	24,2	265	7,12	4,14	2,98
		Tapio	65	502	31,8	29,1	24,3	326	7,23	4,08	3,15
Norway spruce	MT	Baseline	72	881	38,6	25,9	23,1	374	6,49	4,25	2,23
		RPD	76	875	41,5	26,7	23,9	413	6,61	4,64	1,98
		Tapio	69	571	29,9	27,2	21,8	278	5,64	3,62	2,03
Norway spruce	OMT	Baseline	62	879	46,3	28,8	27,7	514	10,73	7,53	3,20
		RPD	65	745	45,1	31,1	28,4	508	10,48	7,68	2,80
		Tapio	56	526	33,3	30,2	25,4	346	9,09	6,20	2,89

The different wood assortments considered in the study are defined as sawnwood, energy wood, paper and packaging. The wood raw material allocation (m^3/ha/y) per each wood assortment in the baseline is on average 29% sawnwood, 33% paper, 16% packaging materials, 22% energy. The proportions vary between regimes, depending on how much sawlog and pulpwood the stand produces. For example with an increased rotation length, the annual sawlog yield increases, while the pulpwood yield decreases. The changes in the wood raw material allocation in each scenario, in relation to the baseline, along with the average wood allocation (m^3/y/ha) of the baseline, are presented in the following Table 9.

Table 9. Scenario average wood allocation m^3 / ha / y.

	Sawnwood	**Paper**	**Energy**	**Packaging**
I. Baseline	29 %	33 %	22 %	16 %
II. RPD	+	-	-	-
IIIa. Sawlog	+	*Unchanged*	*Unchanged*	-
IIIb. Energy	*Unchanged*	*Unchanged*	+	-
IV. Tapio	-	-	-	-

In the baseline the wood allocation is the following:

- The sawlog yield (MAIsl) is accounted so that
  - 50 % goes towards sawnwood;
  - 13 % goes to paper production;
  - 7 % goes to packaging production;
  - 30 % is used for energy.
- The pulpwood yield (MAIpw) is divided so that
  - 60 % goes towards paper production;
  - 30 % is allocated for packaging purposes;
  - 10 % is allocated to energy use.

Proportionally paper, energy and packaging stay the same in baseline, RPD and Tapio, while in the two end-use scenarios, Sawlog and Energy, the proportions change. The climatic benefits of forestry depend heavily on the use of wood raw material and the wood-based products, and therefore these two end-use scenarios are also considered, in which the product mix changes, and pulpwood for packaging purposes is reallocated to other wood assortments. The reduction is determined on the basis of how much less wood raw material for paper, packaging and energy purposes is available when the price of pulpwood decreases, compared to the baseline scenario. This is calculated as (2)

$$R_{wrm} = (0.5 * MAIsl_{bl} + MAIpw_{bl}) - (0.5 * MAIsl_{IFC} + MAIpw_{IFC}) \quad (2)$$

where R_{wrm} is the reduced amount of wood raw material available for paper, packaging and energy.

In the RPD scenario the reduction is equally burdened on paper, packaging and energy, whereas in the two end-use scenarios, Sawlog and Energy, the reduction is burdened on packaging alone. Tapio is somewhat different from the other scenarios, as it is based on the silvicultural guidelines, rather than the economically optimal forest management practices. The wood assortment allocation in Tapio is proportionally fixed to the baseline, in order to examine the climatic impacts of producing the same product mix as in the baseline, but under Tapio management. In absolute terms, the wood yields under the Tapio regime are lower than in the baseline, and therefore the amount of wood allocated per each wood assortment is lower as well.

5.6 Calculation of forest and forest product carbon pools

The first climatic indicator will be the combined carbon pool of forests and forest products. The carbon pools represent the theoretical sustainable level that each scenario could maintain, based on the methodology of the steady-state framework. This allows the comparison of scenarios to one another. The product carbon pools do not grow but remain constant within each scenario, so that the size of the product pool is only determined by the products' estimated lifespans. To compare products which have vastly different length lifecycles, an accounting method needs to be established, which is discussed later. This is important, as the benefits from storing carbon depend heavily on the product lifespan, as long-lived products such as wood used for construction, can store carbon for decades.

The pulp yield is assumed 50 % for chemical pulp, and 95 % for mechanical pulp production. The overall pulp yield is calculated as a weighted average based on the Finnish production figures (Finnish Forest Industries 2011), and therefore the average pulp yield is assumed to be 61 %. The 61 % yield implies that from each cubic meter of wood used for pulping, 39 % of the wood content is lost in the manufacturing process. This lowers both the product carbon pools and the avoided emission, as only the wood content of the final product can be considered. For energy wood and sawlogs no losses are assumed.

The carbon content of wood is assumed 50 % of the dry weight of the wood. This is widely mentioned and used in many previous studies and literature (Pingoud et al.

2010, Lindblad and Verkasalo 2001, Laturi et al. 2008). In empirical research, the actual carbon content has been observed to be in the range of 46.27% to 49.97% for selected hardwood species, and from 47.21% to 55.2% on selected softwood species (Lamlom and Savidge 2003). The dry density of wood is assumed to be 0.4 t / m^3 for both Norway Spruce and Scots Pine. Based on these assumptions, the carbon content of 1 m^3 of wood is 200 kg. Carbon (C) is converted in to carbon dioxide (CO_2) by a factor of 44/12 (~3.67).

The assumed recycling rate for fibre-based packaging materials and paper is 87%, based on end-of-life management statistics on Finland (Eurostat 2010). The cellulose fibre is expected to be recycled six times, before wearing off completely. The length of each cycle is assumed as three months for both paper and packaging. Few public studies on the lifespan of recycled fibre exist. However, in a University of Lappeenranta thesis, Jernström (2002) estimated that in Finland, recycled newspaper is typically 1½ months old when reaching the deinking plant, whereas magazine paper is much older, from eight months up to a year. According to UNFCCC (2003), on average paper and paper products decay within five years. Buchanan and Levine (1999) have used three years for paper products and 40 years for solid wood products in their study. PAS 2050 lifecycle inventory methodology allows credits in the carbon footprint for delayed emissions, if the product’s lifespan is more than one year. For example Nors et al. (2009) have assumed a lifespan of less than one year for newspaper and magazine prints. They point out however, that it would not be unusual for some people to store magazines for years. Eriksson et al. (2010) on the other hand assumed an average lifespan of two years for carton in Europe. Given this, the assumed lifespan of three months per cycle seems more than reasonable. Because of the uncertainty, sensitivity analysis on the lifespan and the recycling rates will be carried out to see how they affect the results. The average lifespan of sawnwood is assumed as 40 years (Pingoud et al. 2001).

For simplicity and because of large uncertainties, carbon at landfills or in soil is not considered. For sawnwood, it is assumed that after 40 years all the carbon is released back to the atmosphere. Thus based on the methodology, the carbon storage for sawnwood is calculated by multiplying the amount of carbon in the sawnwood (50 % of the dry weight) by 40. As per the methodology used, the size of the carbon pools is only determined by the estimated lifespan of the product that holds the carbon, hence the recycling of the fibre-based products has to be considered. The assumed recycling rate is applied to a geometric series, which is then divided by the number of uses the fibre has (first use + recycling). This gives the average carbon content of the products over the cellulose fiber’s whole lifecycle, which can then be multiplied by the length of the total lifecycle of the fibre. The formula for the calculation is presented below (3). The multiplier L in a sense, represents the lifespan the product would have to have, in case it was not recycled at all, to be equally as good as the recycled product.

$$L = \frac{\left(\frac{1-r^n}{1-r}\right)}{n} * t \quad (3)$$

where r is the recycling rate for the fibre, n is the number of times the fibre is recycled and t is the total lifespan of the fibre in years.

The forest carbon pool is based on the total biomass of the trees at the forest stands. MOTTI estimates the forest growth in segments of five years. For each five year segment, the average biomass is by calculated by multiplying the annual average, calculated on basis of change in the biomass, by 5. The wood biomass (t/ha) is converted to carbon, by multiplying the biomass by a factor of 0.5, based on the assumption of 50 % carbon content. The cumulative carbon stock over the whole rotation is divided by the rotation length of the stand, to give the sustainable level of carbon (tC/ha), that the steady-state stand can maintain.

5.7 Calculation of avoided emissions

The climatic benefits of forestry vary depending on the management practices as well as the material substitution, as wood is used instead of other materials. For example, when wood raw material is used for energy purposes instead of packaging, there likely is a positive climatic impact from the energy use in itself, as fossil fuels are substituted by wood. However, since the reduced or “lost” amount of fibre-based packaging material is then in turn substituted with other more energy intensive packaging materials, such as plastics, the overall effect could turn out negative.

The climatic impacts of these changes in the wood-use are studied with the help of carbon displacement factors. The carbon displacement factor is an index of efficiency, with which the use of forest biomass reduces the net greenhouse gas emissions to the atmosphere. The carbon displacement factor is defined by Sathre and O'Connor (2008) as (4)

$$DF = \frac{GHGnonwood - GHGwood}{WUwood - WUnonwood} \quad (4)$$

where GHGnonwood and GHGwood are the greenhouse gas emissions resulting from the use of non-wood and wood alternatives, and WUwood and WUnonwood are the amounts of wood remaining in the end-products, expressed in mass units of biogenic C in the wood.

The resulting amount of avoided emissions achieved by the wood-use is expressed in tons of carbon. A displacement factor of zero would indicate that the wood alternative is just as good as the non-wood alternative, while a displacement factor of 1 would mean that by utilizing wood with a carbon content of 1 ton (~5 m^3 or ~2 t of roundwood), an emission reduction of 1 ton of C could be achieved. In this study the annual wood allocations are applied to the displacement factors (t/ha/y of wood in final product multiplied by displacement factor for the product) to represent the annual avoided emissions from wood use in tC / ha / y.

The displacement factors used for the calculation of avoided emissions will be 2 for sawnwood (Sathre and O'Connors 2008) and 0.8 for paper and energy wood (Sathre and O'Connors 2008, Pingoud et al. 2010). Based on the literary analysis in chapters 4.3, it is reasonable to assume that fibre-based packaging materials have an overall positive climatic impact compared to the use of alternative materials, especially in Finland as the national recycling and energy systems are highly favourable to wood use. Therefore a displacement factor of 1.5 for packaging materials will be applied. For example in the case of liquid packaging board, based on the carbon content of the fibre-based products and the greenhouse gas emissions compared to alternatives, displacement factors as high as 3 – 4 could be calculated. As with the carbon pools, a sensitivity analysis will be carried out to see how changing the displacement factor, i.e., altering how good of an alternative the fibre-based packaging is assumed to be affects the results. The critical values for displacement factors where the avoided emissions between the baseline and the alternative scenario are at equilibrium will also be determined, in order to see how far they are from the assumed average of 1.5. This will also allow seeing how realistic it would be to utilize packaging as a way to reduce the overall emissions in each scenario. If the equilibrium displacement factor for packaging is very high in the given scenario, it is unlikely that packaging would be a realistic option whereas a low factor would indicate otherwise.

6 RESULTS

6.1 Forest and forest product carbon pools

The total carbon pools, including the forest and forest products, varied between 157 – 182 tCO_2/ha for Scots Pine on Vaccinium stands and 237 – 242 tCO_2/ha Myrtillus stands. As expected in the light of the previous findings, the carbon pools for the Norway Spruce stands were considerably higher than on the Scots Pine stands, ranging between 222 – 304 tCO_2/ha on Myrtillus sites and 310 – 413 tCO_2/ha on Oxalis Myrtillus sites.

6.1.1 Baseline

In the baseline the average carbon pools for Scots Pine were 174 tCO_2/ha on Vaccinium sites and 238 tCO_2/ha on Myrtillus sites. For Norway Spruce the total pools were 279 tCO_2/ha on Myrtillus sites and 404 tCO_2/ha on Oxalis Myrtillus sites (Figure 12).

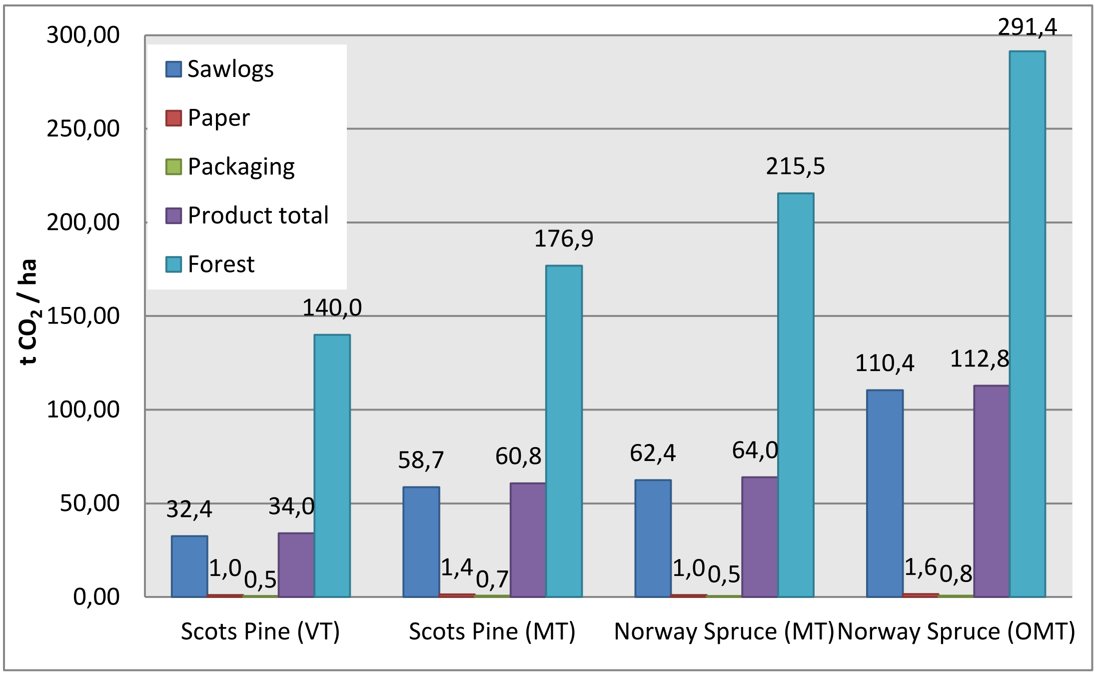

Figure 12. Carbon stocks in the baseline for each species.

The product carbon pools foremost depend on how much high the site sawlog supply is, because the sawlogs are manufactured in to long-lived products, that can capture the carbon for decades. The carbon pools are therefore relatively smaller on stands which produce more pulpwood. OMT Norway Spruce and MT Scots Pine stands both produced relatively more sawlogs than MT Norway Spruce or VT Scots Pine stands, and it can be observed that on these stands with relatively higher share of sawlogs, the product pools also contributed more to the total pools.

In Scots Pine stands, packaging accounts for 1.2 – 1.5 % of the total product pools, while in the Norway Spruce stands their share is less than a percent. Pulp products combined contributed between 2.1 – 4.6 % to the product pools, while all wood products together represented some 19.5 – 27.9 % of the total carbon pools, being relatively largest when the most sawnwood is produced. Energy wood is not present, as it is considered not having any carbon storing benefits whatsoever. The detailed carbon pools are presented in Table 10 for each species and site type.

Table 10. Baseline forest product, forest and total carbon pools (tCO_2/ha).

tCO_2/ha	Scots Pine (VT)	Scots Pine (MT)	Norway Spruce (MT)	Norway Spruce (OMT)
Sawnwood	32,4	58,7	62,4	110,4
Paper	1,0	1,4	1,0	1,6
Packaging	0,5	0,7	0,5	0,8
Product total	34,0	60,8	64,0	112,8
packaging, % of total	*1,54 %*	*1,16 %*	*0,81 %*	*0,70 %*
pulp, % of total	*4,61 %*	*3,47 %*	*2,42 %*	*2,10 %*
Forest stock	140,0	176,9	215,5	291,4
Total stock	174,0	237,7	279,5	404,2
% products	*19,54 %*	*25,57 %*	*22,88 %*	*27,91 %*
% forest	*80,46 %*	*74,43 %*	*77,12 %*	*72,09 %*

6.1.2 Reduced pulpwood demand (RDP) scenario

As a result of pulpwood being less valuable, the management regime changed and the average rotation lengths on all the stands were elongated and the relative share of sawlog supply increased. The changes in the raw material yields and rotation length have an effect on both the product and forest carbon pools. The total pools vary between 182 – 239 tCO_2/ha for Scots Pine and 304 – 413 tCO_2/ha for Norway Spruce, showing an overall increase in the range of 0.4 – 8.7% (Table 11).

Table 11. Carbon stock changes from Baseline to RPD regime (tCO_2/ha).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	2,34	*7,2 %*	2,05	*3,5 %*	5,61	*9,0 %*	2,25	*2,0 %*
Paper	-0,05	*-4,4 %*	-0,10	*-7,2 %*	-0,02	*-1,5 %*	-0,07	*-4,6 %*
Packaging	-0,02	*-4,4 %*	-0,05	*-7,2 %*	-0,01	*-1,5 %*	-0,04	*-4,6 %*
Product total	2,28	*6,7 %*	1,90	*3,1 %*	5,59	*8,7 %*	2,14	*1,9 %*
packaging, % of total		*-0,2 %*		*-0,1 %*		*-0,1 %*		*0,0 %*
pulp, % of total		*-0,5 %*		*-0,3 %*		*-0,2 %*		*-0,1 %*
Forest Stock	6,17	*4,4 %*	-1,05	*-0,6 %*	18,78	*8,7 %*	6,40	*2,2 %*
Total stock	8,45	*4,9 %*	0,85	*0,4 %*	24,36	*8,7 %*	8,54	*2,1 %*
% products		*0,3 %*		*0,7 %*		*0,0 %*		*-0,1 %*
% forest		*-0,3 %*		*-0,7 %*		*0,0 %*		*0,1 %*

Notably, the average forest carbon pools decreased for MT Scots Pine, while on the other stands the effects are the opposite. When the price of pulpwood decreased, the silviculture intensified so that more pulpwood was harvested early on, and the number of trees per hectare was considerably less compared to the baseline. Meanwhile the pulpwood price had a relatively small effect on the rotation length, so the overall impact for carbon sequestration remained negative. In all the stands, the relative contribution from pulpwood products decreased as the sawlog supply increased.

In absolute terms, the forest carbon pools grew fastest on the Norway Spruce stands. This resulted in zero, or a marginally negative effect, on product carbon pool share on the Norway Spruce stands. In the Scots Pine stands, the product share of the carbon pools increased by 0.3 – 0.7 %. In absolute terms, the average product carbon pools increased in all cases, as did the forest carbon pools, with the exception of MT Scots Pine. Even so, the increased product pool was able to offset the decreased forest pool, so that in all the stands, the total pools increased between 0.9 – 8.7 %. VT Scots Pine and MT Norway Spruce, which both had lower carbon pools than their counterparts (sites) in the baseline, showed a greater increase in their carbon pools (Figure 13).

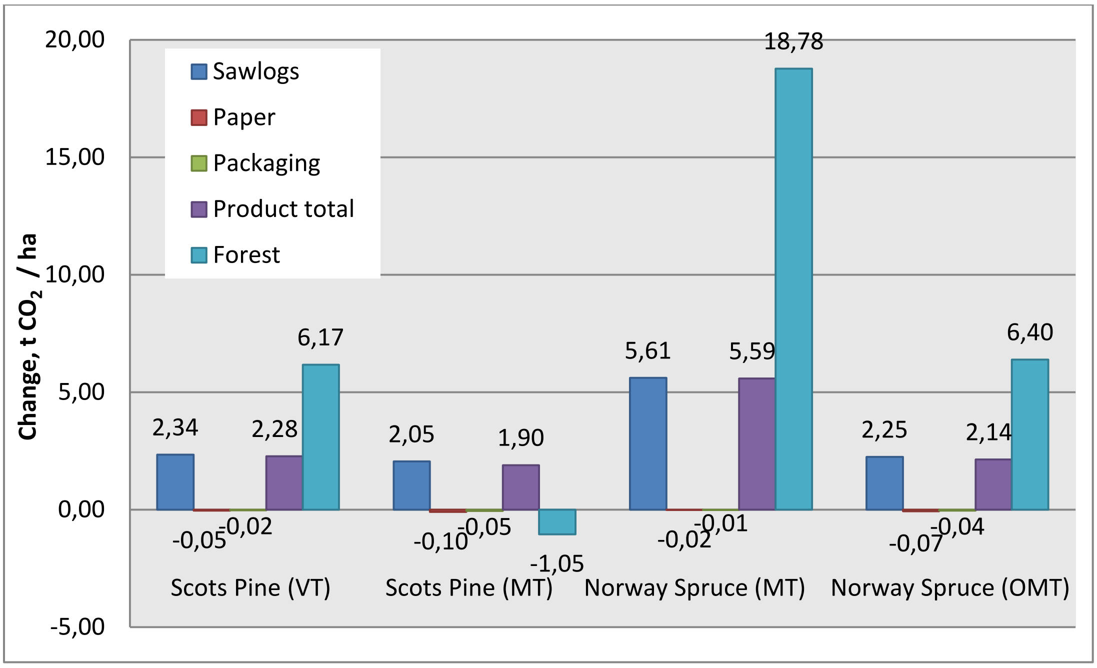

Figure 13. Carbon stock changes from Baseline to RPD scenario.

6.1.3 Sawlog scenario

The first end-use scenario is similar to RPD, with the exception that rather than burdening all the pulpwood products, including energy, the full amount of material reduction is taken from packaging. Hence it is assumed the decreased packaging demand causes a shift in production to sawlogs. Compared to RPD, this shows a relatively small impact, as the management regimes are the same, and as the methodology considers paper from the carbon pool perspective just as good as packaging. Same amount of material goes to paper manufacturing and energy use, as would in the baseline. Since now relatively more wood raw material is used for energy purposes, which has no carbon storing benefits, rather than for packaging which does, the scenario shows slightly worse than RPD, yet better than the baseline. The results are in principle the same as with RPD, however the product carbon pools are approximately 1 – 3 % lower (yet 1.8 – 8.7 % higher than in baseline) as more energy wood is used (Table 12).

Table 12. Carbon stock changes from Baseline to Sawlog scenario (tCO_2/ha).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	2,34	*7,2 %*	2,05	*3,5 %*	5,61	*9,0 %*	2,25	*2,0 %*
Paper	0,00	*0,0 %*	0,00	*0,0 %*	0,00	*0,0 %*	0,00	*0,0 %*
Packaging	-0,09	*-17,3 %*	-0,21	*-30,3 %*	-0,03	*-6,7 %*	-0,17	*-21,8 %*
Product total	2,25	*6,6 %*	1,84	*3,1 %*	5,57	*8,7 %*	2,08	*1,8 %*
packaging, % of total		*-0,3 %*		*-0,4 %*		*-0,1 %*		*-0,2 %*
pulp, % of total		*-0,5 %*		*-0,4 %*		*-0,2 %*		*-0,2 %*
Forest Stock	6,17	*4,4 %*	-1,05	*-0,6 %*	18,78	*8,7 %*	2,08	*2,2 %*
Total stock	8,43	*4,8 %*	0,79	*0,3 %*	24,35	*8,7 %*	8,47	*2,1 %*
% products		*0,3 %*		*0,7 %*		*0,0 %*		*-0,1 %*
% forest		*-0,3 %*		*-0,7 %*		*0,0 %*		*0,1 %*

6.1.4 Energy scenario

In the Energy scenario, rather than management regime changing, it is assumed that the demand simply shifts from packaging to energy use, with no impact on the forest management. As there are no carbon storing benefits with the use of energy wood, the carbon pools are diminished by the amount of carbon in the wood that is now used for energy purposes, rather than packaging. The forest carbon is not affected by this scenario, therefore only the changes in packaging, product and the total carbon pools are presented in Table 13.

Table 13. Carbon stock changes from Baseline to Energy scenario (tCO_2/ha).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Packaging	-0,09	-17,29 %	-0,21	-30,33 %	-0,03	-6,66 %	-0,17	-21,85 %
Product total	-0,09	-0,27 %	-0,21	-0,35 %	-0,03	-0,05 %	-0,17	-0,15 %
Total stock	-0,09	-0,05 %	-0,21	-0,09 %	-0,03	-0,01 %	-0,17	-0,04 %

The effects on the packaging carbon pools vary between 6.7 % – 30 % of lost carbon, while the total product pools decrease between 0.05 % – 0.35 %. The effects are more notable on the Scots Pine stands, as they have a relatively higher share of packaging production than the Norway Spruce stands, due to the higher average pulpwood supply from the stands. On the MT Norway Spruce stands, the pulpwood price drop caused only a very small decrease in the amount of available wood raw material, and therefore only a small amount of fibre shifted from packaging to energy use, causing little effect on the carbon pools.

6.1.5 Tapio scenario

Tapio scenario is somewhat different from the other scenarios in the sense that rather than altering the price of pulpwood, to see how it affects forest management and the wood supply and, subsequently, the carbon pools and the avoided emissions, a totally different kind of management regime is applied on the stands. Instead of maximizing the bareland value of the forest, the regime follows the silvicultural guidelines developed by the Forestry Development Centre Tapio. The allocation of wood raw material is kept proportionally the same as in the baseline, is order to see the climatic impacts of producing the same product mix, as would be produced in the baseline.

Compared to the baseline, the change of the regime had two major effects on the silviculture. For Scots Pine, the silviculture under the economically optimal management is much more intensive, with more frequent and heavier thinnings. For Norway Spruce, the management is more similar between the two regimes, however the average rotation lengths under Tapio were slightly shorter than in the baseline. For MT Scots Pine the change in the regime caused fewer harvests and also slightly elongated the rotation length. All stands under the Tapio management had lower annual wood yields compared to the baseline.

Managing the stands under Tapio caused the total carbon pools to change between 2.0 – 23.1 %. On MT Scots Pine stands the change was positive, as the total pools increased by 2 %, or 4.7 tCO_2/ha, whereas on all the other stands the impacts were negative. On the VT Scots Pine stands the total pool decreased by 17 tCO_2/ha, while on Norway Spruce stands the pools decreased as much as 57.8 – 93.5 tCO_2/ha. The Norway Spruce stands had considerably smaller annual wood yields, and the trees had smaller basal areas and standing volume at the time of the final harvest, hence the impact was much more substantial (Figure 14).

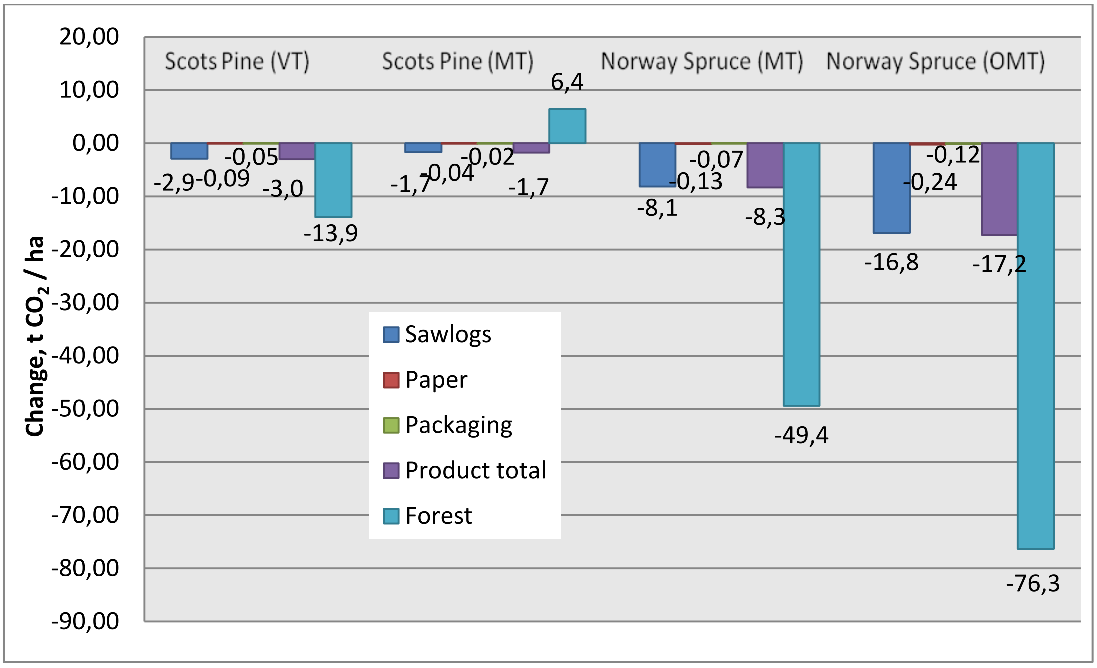

Figure 14. Carbon pool change from Baseline to Tapio.

The product pools showed a sharp decrease as well. On one stand however, the decreased product pool was offset by the increased forest pool, as was the case with MT Scots Pine, so that the stand showed an overall positive change in the carbon pools. It can also be observed, that on all the stands, the product pools changed relatively less than the forest pools, and therefore the total pools were more affected by the rate of carbon sequestration in the forests, than the changes in the raw material yields. The effects were either the opposite, in the case of Scots Pine, or much less dramatic, under the economically optimal forest management when the pulpwood price decreased. The share of wood product pools from the total carbon pools was higher than in the baseline on VT Scots Pine and the Norway Spruce stands. Because the allocation of wood raw material was kept proportionally fixed to the baseline, the contribution of each wood assortment within the product pool is the same as in the baseline. The results are presented below in Table 14.

Table 14. Carbon stock change from Baseline to Tapio regime (tCO_2/ha).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	-2,89	*-8,9 %*	-1,68	*-2,9 %*	-8,13	*-13,0 %*	-16,85	*-15,3 %*
Paper	-0,09	*-8,9 %*	-0,04	*-2,9 %*	-0,13	*-13,0 %*	-0,24	*-15,3 %*
Packaging	-0,05	*-8,9 %*	-0,02	*-2,9 %*	-0,07	*-13,0 %*	-0,12	*-15,3 %*
Product total	-3,03	*-8,9 %*	-3,03	*-2,9 %*	-8,33	*-13,0 %*	-17,21	*-15,3 %*
packaging, % of total	*1,54 %*	*0,0 %*	*1,16 %*	*0,0 %*	*0,81 %*	*0,0 %*	*0,70 %*	*0,0 %*
pulp, % of total	*4,61 %*	*0,0 %*	*3,47 %*	*0,0 %*	*2,42 %*	*0,0 %*	*2,10 %*	*0,0 %*
Forest Stock	-13,93	*-9,9 %*	6,42	*3,6 %*	-49,42	*-22,9 %*	-76,29	*-26,2 %*
Total stock	-16,96	*-9,7 %*	4,68	*2,0 %*	-57,74	*-20,7 %*	-93,50	*-23,1 %*
% products	19,72 %	*0,2 %*	24,36 %	*-1,2 %*	25,08 %	*2,2 %*	30,77 %	*2,9 %*
% forest	80,28 %	*-0,2 %*	75,64 %	*1,2 %*	74,92 %	*-2,2 %*	69,23 %	*-2,9 %*

6.1.6 Sensitivity analysis

Sawnwood has approximately 12 – 23 times higher carbon storing potential per cubic meter of harvested wood used, than packaging materials or other pulpwood products. This is based on the assumptions about the life spans, the sawnwood yield from sawlogs and the pulp yields from pulping and the end-of-life management options, as discussed in the methodology chapter. With a longer lifespan and a higher recycling rate, the gap could be considerably reduced. For example by doubling the lifespan of a pulp product to 6 months from the assumed 3, the carbon storing potential of sawnwood would only be 6 – 11 times higher than that of pulpwood, depending whether the pulp is chemically or mechanically pulped. The significance of the recycling and the lifespan of the pulpwood products is illustrated below, by altering the lifespan and recycling rate of the fibre-based packaging materials using the overall average pulp yield in Finland (Figure 15).

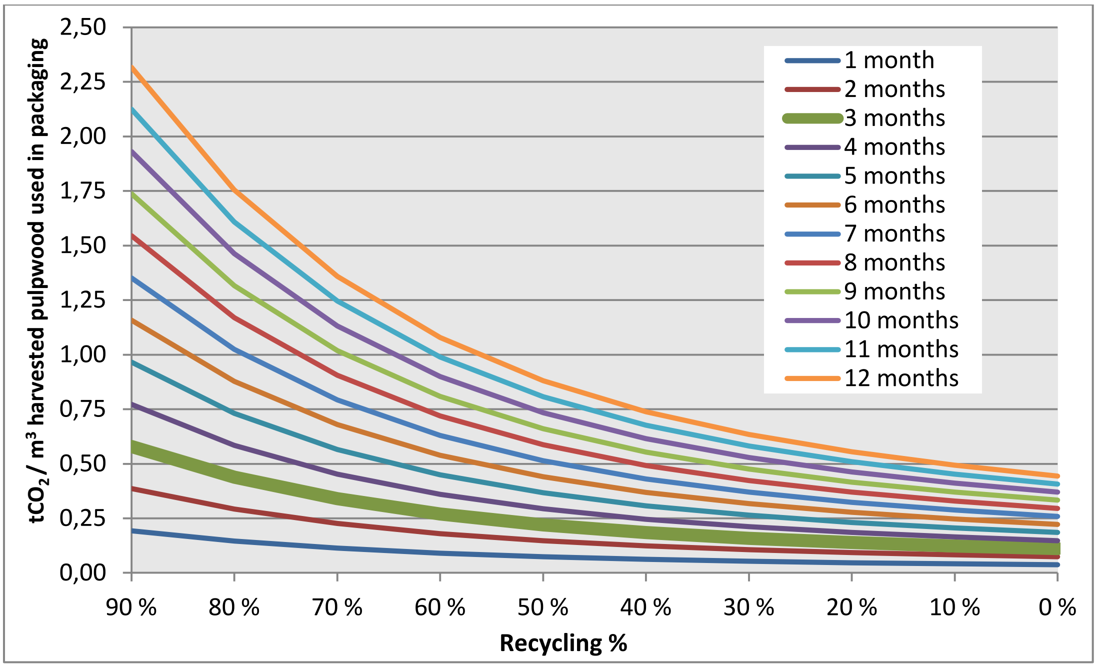

Figure 15. Carbon bound in packaging materials depending on the lifespan and recycling rate.

6.2 Avoided emissions from wood use

The climatic impacts of the changes in the wood-use are studied with the help of carbon displacement factors obtained through an extensive literature analysis. In a sense, the displacement factor represents an index of efficiency, with which the use of forest biomass reduces the net greenhouse gas emissions to the atmosphere, by utilizing wood instead of alternative materials.

The avoided emissions in the scenarios varied on average between 3.2 – 3.5 tCO_2/ha for Scots Pine on Vaccinium stands and 5.5 – 5.6 tCO_2/ha Myrtillus stands, and between 4.6 – 5.6 tCO_2/ha for Norway Spruce on Myrtillus stands and 7.7 – 9.1 tCO_2/ha on Oxalis Myrtillus stands. The variation was considerably larger for Norway Spruces, due to the Tapio regime having a relatively larger impact on the wood supply on the Norway Spruce stands.

6.2.1 Baseline

In the baseline the avoided emissions for Scots Pine were 3.50 tCO_2/ha on Vaccinium site and 5.63 tCO_2/ha/y on Myrtillus site. For Norway Spruce the avoided emissions were 5.31 tCO_2/ha/y on Myrtillus sites and 9.05 tCO_2/ha/y on Oxalis

Myrtillus sites (Figure 16). The amount of avoided emissions is relatively highest on stands that produce the most sawnwood, as it is assumed that sawnwood carries the highest substitution benefits. However, since the wood products are now compared to alternative materials with the same functional value or use, such as plastics in the case of packaging materials, rather than to one another, in which case sawnwood benefits from the considerably longer lifecycle, the importance of the other wood products is now more evident.

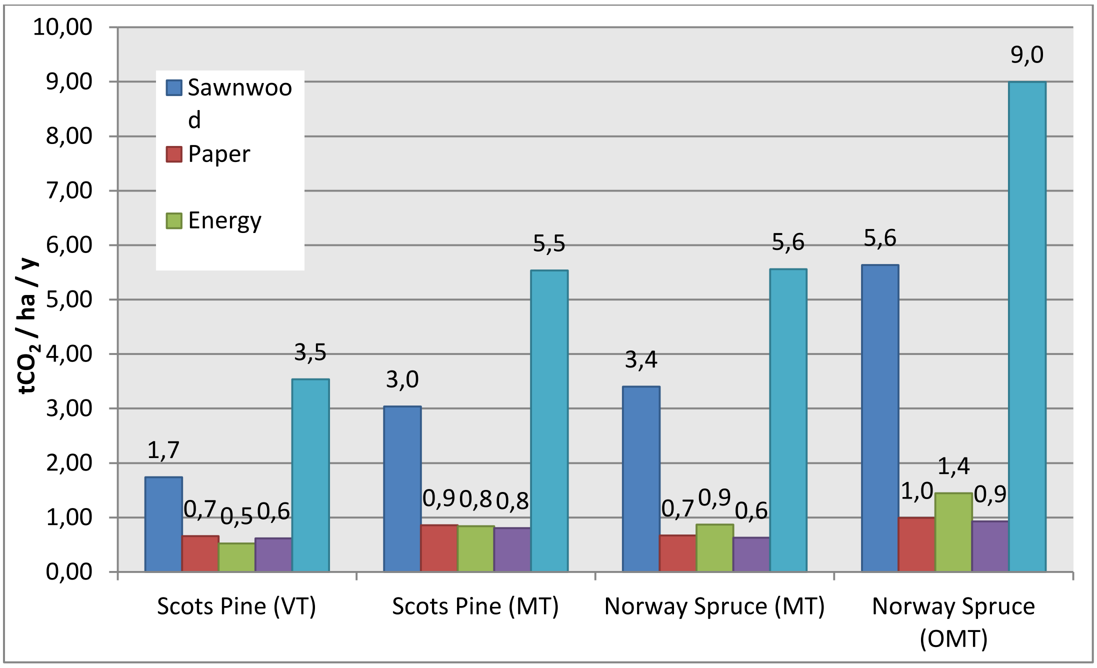

Figure 16. Avoided emissions in the Baseline.

The packaging materials contribute between 15.4 – 18.4 % (0.6 – 0.9 tCO_2/ha/y) of the total avoided emissions on the Scots Pine stands, which produce relatively more pulpwood than the Norway Spruce stands, on which the packaging materials accounted between 10.8 – 12 % (0.6 – 1.0 tCO_2/ha/y) of the total avoided emissions (Table 15).

Table 15. Avoided emissions in the Baseline (tCO_2/ha/y).

tCO_2/ha/y	Scots Pine (VT)	Scots Pine (MT)	Norway Spruce (MT)	Norway Spruce (OMT)
Sawnwood	1,62	2,93	3,12	5,52
Paper	0,69	0,92	0,68	1,04
Energy	0,55	0,91	0,88	1,51
Packaging	0,64	0,86	0,63	0,97
Total	3,50	5,63	5,31	9,05
% Sawnwood	*46,34 %*	*52,13 %*	*58,74 %*	*61,04 %*
% Paper	*19,60 %*	*16,40 %*	*12,75 %*	*11,48 %*
% Energy	*15,69 %*	*16,10 %*	*16,56 %*	*16,72 %*
% Packaging	*18,37 %*	*15,37 %*	*11,95 %*	*10,76 %*

OMT Norway Spruce stands clearly show the highest avoided emissions in the baseline. The superiority of the stands is no longer as evident as before, as MT Scots Pine has higher associated avoided emissions than MT Norway Spruce, which earlier showed superior carbon pools than the MT Scots Pine stand. Interestingly the MT Norway Spruce stands have approximately 12.8 % lower annual wood yield, and the product carbon pools are almost the same between the two in the baseline. The MT Norway Spruce produces more sawlogs however, which is more beneficial for the avoided emissions (and the carbon pools), and thus the avoided emissions are only about 5.7 % lower, despite the lower wood yield.

6.2.2 Reduced pulpwood demand (RPD) scenario

The total avoided emissions in the scenario varied between 3.5 – 5.5 tCO_2/ha/y for Scots Pine and 5.6 – 9.0 tCO_2/ha/y for Norway Spruce. The relative share of paper, energy and packaging has now decreased, with varying effects to the overall avoided emissions. The RPD scenario is foremost dependent on the stands to supply more sawlogs, to compensate for the lost amount pulpwood and the decreased avoided emissions thereof.

On stands which had higher relative share of sawlog production in the baseline, the increased amount was not enough and the avoided emissions decreased by 1.6 % (0.09 tCO_2/ha/y) for MT Scots Pine and 0.5 % (0.05 tCO_2/ha/y) for OMT Norway Spruce. On VT Scots Pine and MT Norway Spruce stands however, the increased sawlog production was enough to offset the lost pulpwood. In fact, on the MT Norway Spruce stands, the total avoided emissions increased by as much as 4.7 %, as the pulpwood price drop had relatively little effect on paper, energy and packaging, while the sawlog supply increased considerably (Table 16).

Table 16. Avoided emissions change from baseline to RPD (tCO_2/ha/y).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	0,12	7,23 %	0,10	3,50 %	0,28	8,99 %	0,11	2,04 %
Paper	-0,03	-4,36 %	-0,07	-7,24 %	-0,01	-1,46 %	-0,05	-4,58 %
Energy	-0,02	-4,36 %	-0,07	-7,24 %	-0,01	-1,46 %	-0,07	-4,58 %
Packaging	-0,03	-4,36 %	-0,06	-7,24 %	-0,01	-1,46 %	-0,04	-4,58 %
Total	0,04	1,01 %	-0,09	-1,64 %	0,25	4,68 %	-0,05	-0,54 %
% Sawnwood		2,85 %		2,72 %		2,42 %		1,58 %
% Paper		-1,04 %		-0,93 %		-0,75 %		-0,47 %
% Energy		-0,83 %		-0,92 %		-0,97 %		-0,68 %
% Packaging		-0,98 %		-0,87 %		-0,70 %		-0,44 %

6.2.3 Sawlog scenario

RPD and Sawlog scenarios share the same management regime, however now the full effect of the decreased pulpwood supply is burdened on the packaging materials. Because packaging materials have better substitution benefits than paper or energy use, this scenario shows worse than the RPD, in which the relative share of packaging materials was higher. The total avoided emissions range between 3.51 – 5.47 tCO_2/ha/y for Scots Pine and 5.55 – 8.95 tCO_2/ha/y on Norway Spruce.

The shift in demand and the subsequent increase in the sawlog production caused the avoided emissions from packaging materials to decrease by 17.3 – 30.3 % on the Scots Pine and 6.7 – 21.9 % on the Norway Spruce stands, now accounting for only 11.0 – 15.2 % of the total avoided emissions for Scots Pine and 8.5 – 10.7 % for the total avoided emissions for Norway Spruce.

The increased amount of sawlog production on the VT Scots Pine stand was just barely able to offset the overall impact by 0.2 %, whereas the MT Norway Spruce stand still showed clearly higher avoided emissions due to the increased sawlog supply. The MT Scots Pine and OMT Norway Spruce stands again showed a negative overall impact, and slightly more so, than in the RPD scenario. On some stands it is thus possible for the demand to shift from packaging or pulpwood products to sawnwood, without a negative overall impact. The likelihood of this seems to depend on the relative share of sawlog production in the start (Table 17).

Table 17. Change in avoided emissions from baseline to sawlog scenario (tCO_2/ha/y).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	0,12	7,23 %	0,10	3,50 %	0,28	8,99 %	0,11	2,04 %
Paper	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %
Energy	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %
Packaging	-0,11	-17,29 %	-0,26	-30,33 %	-0,04	-6,66 %	-0,21	-21,85 %
Total	0,01	0,17 %	-0,16	-2,84 %	0,24	4,48 %	-0,10	-1,11 %
% Sawnwood		3,26 %		3,40 %		2,53 %		1,94 %
% Paper		-0,03 %		0,48 %		-0,55 %		0,13 %
% Energy		-0,03 %		0,47 %		-0,71 %		0,19 %
% Packaging		-3,20 %		-4,35 %		-1,27 %		-2,26 %

6.2.4 Energy scenario

The results in the energy scenario for the avoided emissions are similar to those earlier observed on the carbon pools. Without exception, the total avoided emissions decreased, as the demand shifted from packaging materials to energy use. The overall impact was between 0.4 – 0.6 % for Scots Pine and 0.1 – 0.3 % for Norway Spruce. The effects were relatively smaller on the Norway Spruce stands, as these stands had a higher contribution coming from the sawnwood products and hence were less affected, than the Scots Pine stands (Table 18).

Table 18. Change in the avoided emissions from baseline to energy scenario (tCO_2/ha/y).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %
Paper	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %	0,00	0,00 %
Energy	0,10	17,83 %	0,23	25,50 %	0,04	4,23 %	0,19	12,38 %
Packaging	-0,11	-17,29 %	-0,26	-30,33 %	-0,04	-6,66 %	-0,21	-21,85 %
Total	-0,01	-0,38 %	-0,03	-0,56 %	-0,01	-0,09 %	-0,03	-0,28 %
% Sawnwood		0,18 %		0,29 %		0,06 %		0,17 %
% Paper		0,07 %		0,09 %		0,01 %		0,03 %
% Energy		2,87 %		4,22 %		0,72 %		2,12 %
% Packaging		-3,12 %		-4,60 %		-0,79 %		-2,33 %

6.2.5 Tapio scenario

The Tapio regime produces considerably less sawlogs and pulpwood than the baseline. Since now only the annual wood yields, and the associated avoided emissions from the substitution are considered, the scenario shows considerably worse results, than the baseline. To compare the effects, it is assumed that the same product mix is produced here under the silvicultural guidelines developed by Tapio, as would be under the economically optimal regime of the baseline.

The total amount of avoided emissions under Tapio ranged between 3.19 – 5.47 tCO_2/ha/y on the Scots Pine and 4.62 – 7.67 tCO_2/ha/y on the Norway Spruce stands. The effects of the management regime were stronger on the Norway Spruce stands and therefore they show a sharper 13 – 15.2 % decrease in the avoided emissions. The impact on the Scots Pine stands was more modest, between 2.9 – 8.9 %, yet still considerable (Table 19).

Table 19. Avoided emissions change from baseline to Tapio scenario (tCO_2/ha/y).

	Scots Pine (VT)		Scots Pine (MT)		Norway Spruce (MT)		Norway Spruce (OMT)	
Change	tCO_2	%	tCO_2	%	tCO_2	%	tCO_2	%
Sawnwood	-0,14	-8,91 %	-0,08	-2,86 %	-0,41	-13,02 %	-0,84	-15,26 %
Paper	-0,06	-8,91 %	-0,03	-2,86 %	-0,09	-13,02 %	-0,16	-15,26 %
Energy	-0,05	-8,91 %	-0,03	-2,86 %	-0,11	-13,02 %	-0,23	-15,26 %
Packaging	-0,06	-8,91 %	-0,02	-2,86 %	-0,08	-13,02 %	-0,15	-15,26 %
Total	-0,31	-8,91 %	-0,16	-2,86 %	-0,69	-13,02 %	-1,38	-15,26 %
% Sawnwood		0,00 %		0,00 %		0,00 %		0,00 %
% Paper		0,00 %		0,00 %		0,00 %		0,00 %
% Energy		0,00 %		0,00 %		0,00 %		0,00 %
% Packaging		0,00 %		0,00 %		0,00 %		0,00 %

6.3.6 Sensitivity analysis and critical displacement factors

Carrying out the sensitivity analysis shows the point where the use of fibre-based packaging materials becomes a climatic benefit. It is carried out by changing the displacement factor of the fibre-based packaging material between 0 and 4. From the sensitivity analysis, it can be observed that rather quickly, even using moderate displacement factors, the use of packaging materials starts to increase the overall avoided emissions.

In the RPD scenario MT Scots Pine and OMT Norway Spruce show that even using a displacement factor of zero, the shift from baseline would have an adverse impact on the the avoided emissions. On the other hand, in VT Scots Pine stands, the decreased fibre-based packaging supply would only have a negative impact, in case the substitution benefits were considerably high (over 3 and up). For some specific purposes, substituting alternative materials with fibre packaging could be this beneficial, but at a large-scale it is highly unlikely. MT Norway Spruce on the other hand produced so much more sawlogs, that on these stands, it is impossible to see any achievable benefits in regard to the baseline (Figure 17).

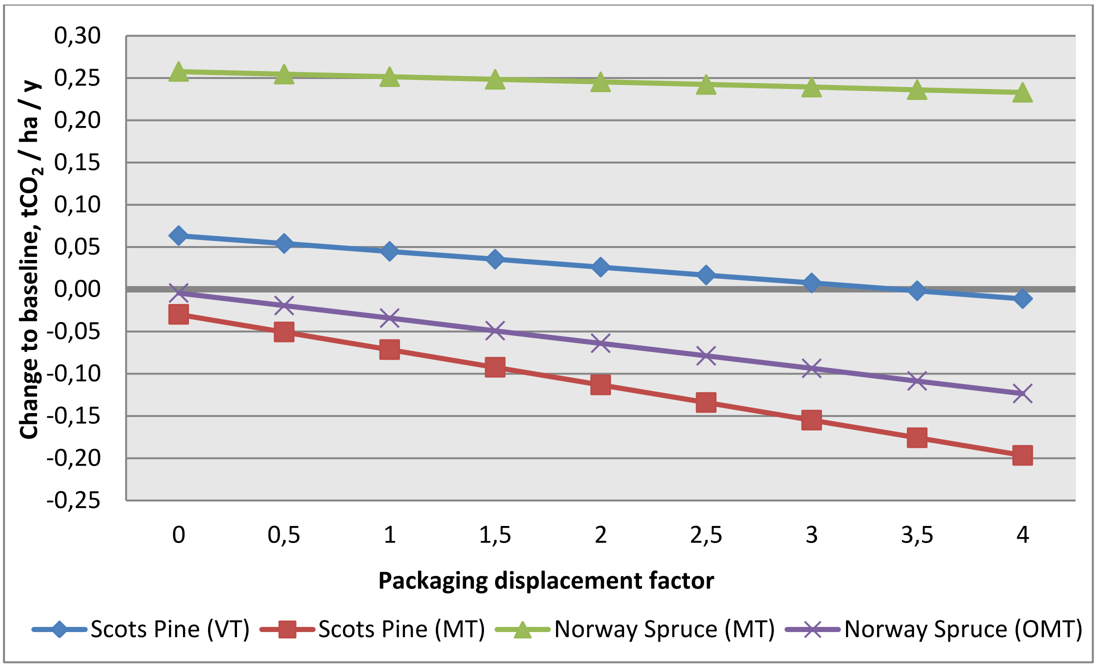

Figure 17. RPD scenario sensitivity analysis of avoided emissions compared to the baseline by altering the packaging displacement factor.

In the Sawlog end-use scenario, the avoided emissions react more strongly to the change of the displacement factor, as it now affects a bigger portion of the total wood yield. The decreased demand for fibre-based packaging, and the subsequent decrease of available wood raw material, is now fully burdened on packaging, as opposed to the RPD scenario, in which paper and energy used were also affected. This causes fibre-based packaging first showing a negative impact, which then quickly and steeply changes to positive. VT Scots Pine showed earlier just barely positive total change in the avoided emissions with the displacement factor of 1.5, and it can now be observed, that if slightly more greenhouse gas emissions could be avoided, with the use of fibre-based packaging, the overall impact would have been negative as well. MT Norway Spruce again clearly shows a positive change, however now decreasing more rapidly. MT Scots Pine and OMT Norway Spruce would benefit from more fibre-based packaging, even using displacement factors under 1 (Figure 18).

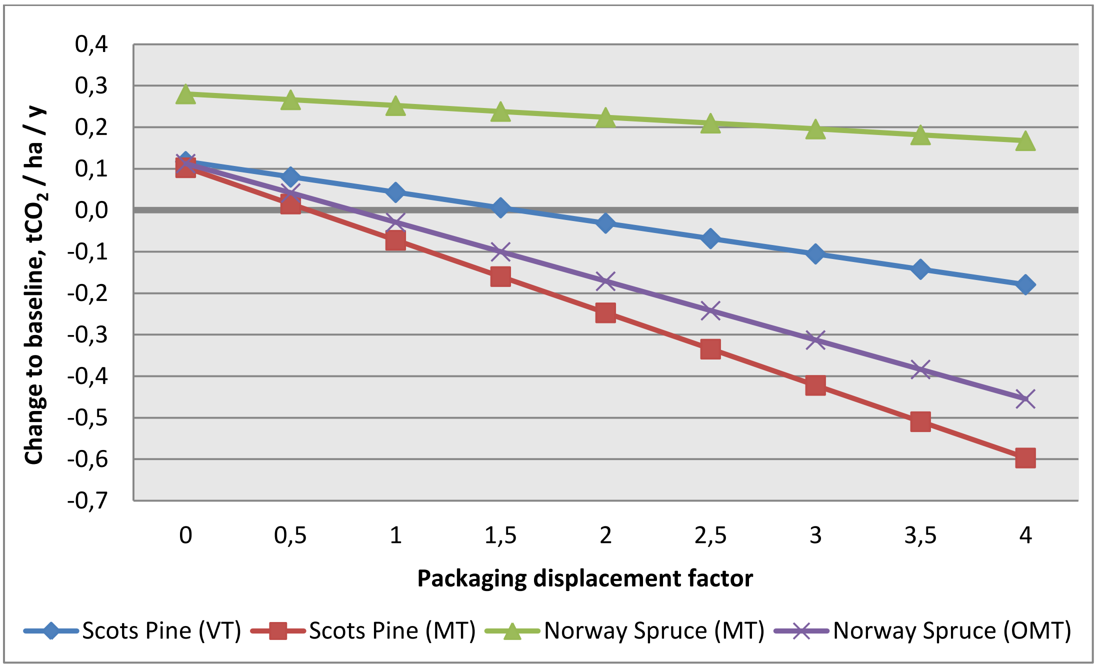

Figure 18. Sawlog scenario sensitivity analysis of avoided emissions compared to the baseline by altering the packaging displacement factor.

Fibre-based packaging on all stands surpasses energy use at the same point. The difference is on how steeply before and after the point, fibre-based affects the avoided emissions. When fibre-based packaging can be utilized in such a manner that it displaces emissions by a factor of 1.3 or higher, the use of wood for packaging rather than energy is preferable (Figure 19).

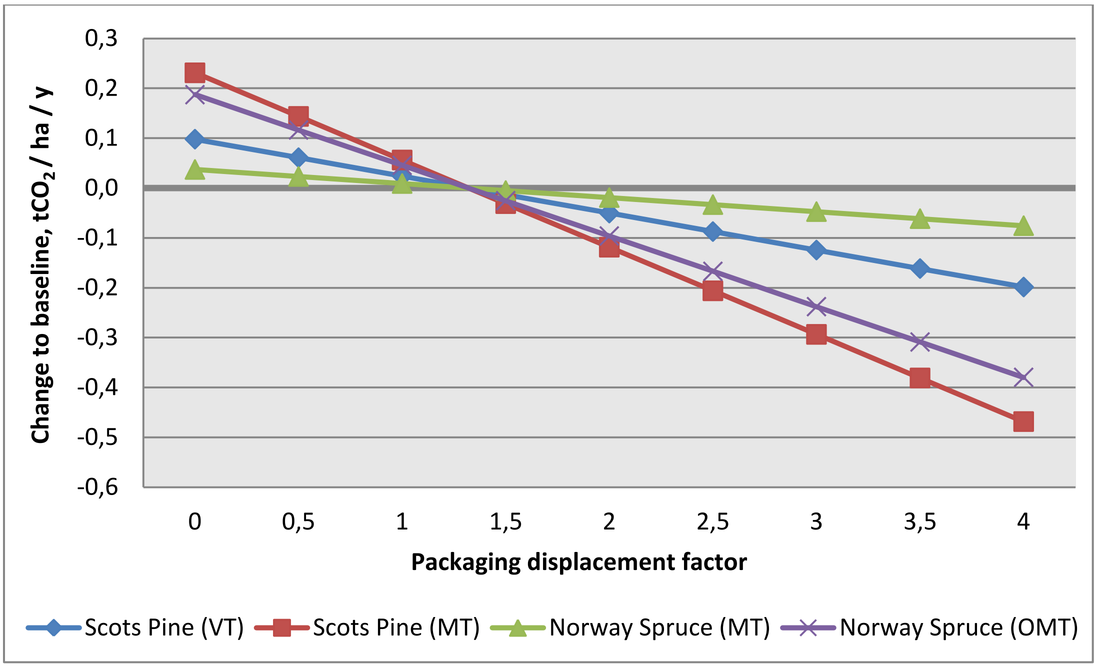

Figure 19. Energy scenario sensitivity analysis of avoided emissions compared to the baseline by altering the packaging displacement factor.

As for the Tapio scenario, it can be observed that the scenario could only achieve higher avoided emissions than the baseline, by assuming an unrealistically low displacement factor for fibre-based packaging. In fact, it would only be as good as the baseline, if the use of fibre-based packaging materials was extremely unfavorable, compared to the alternative packaging materials. It should be noted however, that due to the different approaches (economically optimal management in other scenarios vs. the silvicultural guidelines here), the implications here are not straightforward (Figure 20).

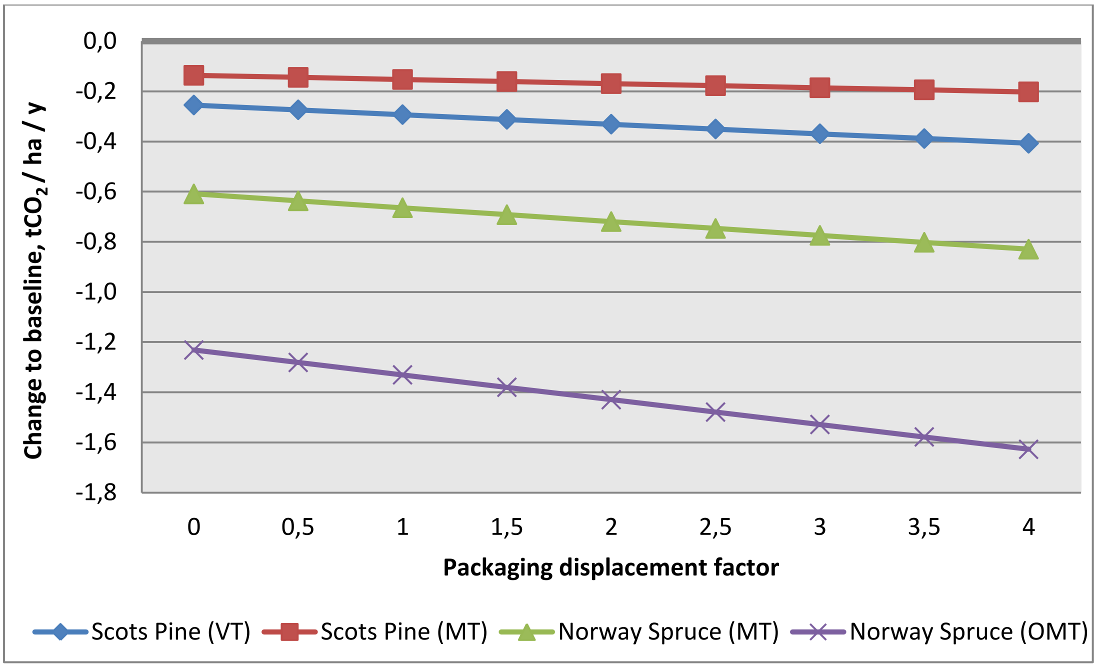

Figure 20. Tapio scenario sensitivity analysis of avoided emissions compared to the baseline by altering the packaging displacement factor.

6.3 Integrated analysis of the carbon pools and the avoided emissions

In some cases the climatic benefits conflict with each other. For instance a stand in an alternative scenario could have higher carbon pools, but lower avoided emissions, than in the baseline. Because of the avoided emissions from the annual wood use, at some point in the future, the avoided emissions could close the gap between steady-state carbon, after which point the scenario with the higher avoided emissions, would become the more favorable one.

In some cases there are also win-win scenarios, situations when both the pools and the avoided emissions react positively to the change. There were four such instances, two associated with the RPD and two with the Sawlog scenarios. The VT Scots Pine and MT Norway Spruce stands both had higher carbon pools and avoided emissions, whereas the MT Scots Pine and OMT Norway Spruce stands had higher carbon pools but lower avoided emissions. It can be estimated that the MT Scots Pine stand could close the gap between the carbon pools in only 5 – 9 years, whereas for the OMT Norway Spruce it would take longer, between 85 – 174 years, yet still within the range of the typical 100 year time horizon often used in lifecycle studies.

Without exception, the Energy scenario showed lower carbon pools as well as lower avoided emissions in regard to the baseline, and therefore it was a lose-lose scenario across the board. Tapio is similar, though in absolute terms showed even worse results than the Energy scenario. In the case of MT Scots Pine however, the carbon pools were some 4.68 tCO_2/ha higher than in the baseline. The avoided emissions at the same time were 0.16 tCO_2/ha/y lower and therefore by utilizing wood to substitute for other more energy intensive materials, the carbon pool gap between the baseline and Tapio would be closed in no more than 29 years. The summary table of the carbon pools and the avoided emissions, along with how many years it would take to compensate for the difference, are presented below in Table 20.

Table 20. Comparison between the carbon pools (tCO_2/ha) and the avoided emissions greenhouse gas emissions (tCO_2/ha/y).

Change to baseline	CO_2/ha	CO_2/ha/y	Years to compensate
Reduced pulpwood demand			
Scots Pine (VT)	8,45	0,04	Win-Win
Scots Pine (MT)	0,85	-0,09	9
Norway Spruce (MT)	24,36	0,25	Win-Win
Norway Spruce (OMT)	8,54	-0,05	174
Sawlogs			
Scots Pine (VT)	8,43	0,01	Win-Win
Scots Pine (MT)	0,79	-0,16	5
Norway Spruce (MT)	24,35	0,24	Win-Win
Norway Spruce (OMT)	8,47	-0,10	85
Energy			
Scots Pine (VT)	-0,09	-0,01	Lose-Lose
Scots Pine (MT)	-0,21	-0,03	Lose-Lose
Norway Spruce (MT)	-0,03	-0,01	Lose-Lose
Norway Spruce (OMT)	-0,17	-0,03	Lose-Lose
Tapio			
Scots Pine (VT)	-16,96	-0,31	Lose-Lose
Scots Pine (MT)	4,68	-0,16	29
Norway Spruce (MT)	-57,74	-0,69	Lose-Lose
Norway Spruce (OMT)	-93,50	-1,38	Lose-Lose

7 DISCUSSION

7.1 Summary of results

The use of wood raw material for fibre-based packaging and other wood-based products seems favorable, when considering climate change mitigation aspect of forestry and wood use. Fibre-based packaging materials displace fossil carbon emissions by substituting more energy intensive materials, and delay biogenic carbon re-emissions to the atmosphere at least until the end of their lifecycle.

The results showed that the product carbon pools were in the range of 20 – 30 % of total pools, hence it is fair to say that the forest products are significant carbon sinks. The amount of carbon bound to fibre-based packaging materials ranged between 0.7 – 1 % of the product pools, or 0.5 – 0.9 % of the total pools. It is quite significant, considering that the carbon in packaging and pulpwood products is often neglected, and the opportunities for the delayed emissions from pulp products are not considered or taken in to account.

With the exception of MT Scots Pine, the RPD scenario had the highest carbon pools on all the stands. With MT Scots Pine, Tapio showed some 4.7 tCO_2/ha higher total pools in regard to the baseline. This was due to the higher rate of carbon sequestration in the standing forest stock under the Tapio management. The forest management in the baseline and the RPD for MT Scots Pine stands was much more intensive with more thinnings than under the Tapio management. In the case of RPD and the Sawlog scenarios, the product carbon pools were actually higher than under Tapio management; this was however offset by their lower forest carbon. As for the total carbon pools, on all but MT Scots Pine stands, Tapio proved to be inferior, in the case of Norway Spruce, showing some 20.7 – 23.1 % lower total pools than the baseline. At most, the carbon pools increased by 8.7 %, as was the case in the RPD scenario and the OMT Norway Spruce stands.

As there are no carbon storing benefits associated with the use of energy wood, the Energy scenario showed lower average pools than baseline, RPD and Sawlog on all the stands. While the impacts observed were marginal, it should be noted that any material used for energy purposes, instead of wood products, will decrease the carbon pools and increase the amount of carbon re-entering the atmosphere. If paper and packaging were treated differently, the Sawlog scenario would show better or worse results, depending on which of the products can hold the carbon for longer. The carbon pools are presented in the following summary Table 21, arranged in an order from the highest to the lowest.

Table 21. Carbon pools (tCO_2/ha) summary table, where SW is sawnwood, P is paper, Pa is packaging and Ptot is the product total.

Species	Scenario	SW	P	Pa	Ptot	% Pa	% Pulp	Forest	Total
Scots Pine (VT)	RPD	34,8	1,0	0,5	36,3	1,4 %	4,1 %	146,2	182,5
Scots Pine (VT)	Sawlog	34,8	1,0	0,4	36,3	1,2 %	4,1 %	146,2	182,5
Scots Pine (VT)	Baseline	32,4	1,0	0,5	34,0	1,5 %	4,6 %	140,0	174,0
Scots Pine (VT)	Energy	32,4	1,0	0,4	33,9	1,3 %	4,4 %	140,0	173,9
Scots Pine (VT)	Tapio	29,5	1,0	0,5	31,0	1,5 %	4,6 %	126,1	157,1
Scots Pine (MT)	Tapio	57,0	1,4	0,7	59,0	1,2 %	3,5 %	183,3	242,3
Scots Pine (MT)	RPD	60,7	1,3	0,7	62,7	1,0 %	3,1 %	175,8	238,5
Scots Pine (MT)	Sawlog	60,7	1,4	0,5	62,6	0,8 %	3,0 %	175,8	238,5
Scots Pine (MT)	Baseline	58,7	1,4	0,7	60,8	1,2 %	3,5 %	176,9	237,7
Scots Pine (MT)	Energy	58,7	1,4	0,5	60,6	0,8 %	3,1 %	176,9	237,5
Norway Spruce (MT)	RPD	68,0	1,0	0,5	69,5	0,7 %	2,2 %	234,3	303,9
Norway Spruce (MT)	Sawlog	68,0	1,0	0,5	69,5	0,7 %	2,2 %	234,3	303,8
Norway Spruce (MT)	Baseline	62,4	1,0	0,5	64,0	0,8 %	2,4 %	215,5	279,5
Norway Spruce (MT)	Energy	62,4	1,0	0,5	63,9	0,8 %	2,4 %	215,5	279,5
Norway Spruce (MT)	Tapio	54,3	0,9	0,4	55,6	0,8 %	2,4 %	166,1	221,7
Norway Spruce (OMT)	RPD	112,7	1,5	0,8	114,9	0,7 %	2,0 %	297,8	412,8
Norway Spruce (OMT)	Sawlog	112,7	1,6	0,6	114,9	0,5 %	1,9 %	297,8	412,7
Norway Spruce (OMT)	Baseline	110,4	1,6	0,8	112,8	0,7 %	2,1 %	291,4	404,2
Norway Spruce (OMT)	Energy	110,4	1,6	0,6	112,6	0,5 %	2,0 %	291,4	404,1
Norway Spruce (OMT)	Tapio	93,6	1,3	0,7	95,6	0,7 %	2,1 %	215,1	310,7

The applied default values for displacement factors drive the results about avoided emissions. Based on the literature analysis, sawnwood had the highest applied displacement factor values and therefore scenarios with increased sawlog production generally yield the highest avoided emissions. Fibre-based products were not able to fully compete with sawlog in avoided emissions, but they outperformed energy use clearly. The results from the avoided emissions indicate similarities in the relative superiority of the different scenarios, as the results from the carbon pools. Again the RPD scenario fared well, with the highest associated average avoided emissions achieved on two of the stands. However, unlike with the carbon pools, the interpretation is not as straight forward, as on the other two stands, the avoided emissions in regard to the baseline were lower. On MT Scots Pine and OMT Norway Spruce stands, the avoided emissions in the baseline were slightly higher than in any of the alternative scenarios, as the shift to increased sawlog production or energy use could not offset the diminished packaging production and material substitution thereof. Consequently MT Scots Pine and OMT Norway Spruce stands were also the two stands which showed the smallest increment in sawlog production, when the management regime changed. Sawlogs were not able to offset the lost pulpwood and packaging materials, in these two cases.

As with the carbon pools, Tapio scenario provided the least climatic benefits. Energy use proved worse than the baseline on all the stands. It did however, in the case of MT Scots Pine and OMT Norway Spruce, fare better than the RPD or the Sawlog scenarios. From the resource allocation point of view, the results indicate that it is justified to use wood raw material for packaging purposes, if mitigating climate change is one of the decision making factors. In the calculations, the relative amount of avoided emissions from the use of fibre-based packaging materials was close to the relative amount of raw material allocated to that purposes. Allocating pulpwood to fibre-based packaging was more effective, than allocating the same material to paper or energy purposes. The summary of the avoided emissions, arranged from the highest to the lowest, is presented below in Table 22.

Table 22. Summary of avoided emissions, where CTB is the change to baseline (%).

Species	Scenario	SW	P	E	Pa	Total	CTB	% SW	% P	% E	% Pa
Scots Pine (VT)	RPD	1,74	0,66	0,53	0,62	3,54	1,0 %	49,2 %	18,6 %	14,9 %	17,4 %
Scots Pine (VT)	Sawlog	1,74	0,69	0,55	0,53	3,51	0,2 %	49,6 %	19,6 %	15,7 %	15,2 %
Scots Pine (VT)	*Baseline*	*1,62*	*0,69*	*0,55*	*0,64*	*3,50*	*0,0 %*	*46,3 %*	*19,6 %*	*15,7 %*	*18,4 %*
Scots Pine (VT)	Energy	1,62	0,69	0,65	0,53	3,49	-0,4 %	46,5 %	19,7 %	18,6 %	15,3 %
Scots Pine (VT)	Tapio	1,48	0,62	0,50	0,59	3,19	-8,9 %	46,3 %	19,6 %	15,7 %	18,4 %
Scots Pine (MT)	*Baseline*	*2,93*	*0,92*	*0,91*	*0,86*	*5,63*	*0,0 %*	*52,1 %*	*16,4 %*	*16,1 %*	*15,4 %*
Scots Pine (MT)	Energy	2,93	0,92	1,14	0,60	5,60	-0,6 %	52,4 %	16,5 %	20,3 %	10,8 %
Scots Pine (MT)	RPD	3,04	0,86	0,84	0,80	5,53	-1,6 %	54,9 %	15,5 %	15,2 %	14,5 %
Scots Pine (MT)	Sawlog	3,04	0,92	0,91	0,60	5,47	-2,8 %	55,5 %	16,9 %	16,6 %	11,0 %
Scots Pine (MT)	Tapio	2,85	0,90	0,88	0,84	5,47	-2,9 %	52,1 %	16,4 %	16,1 %	15,4 %
Norway Spruce (MT)	RPD	3,40	0,67	0,87	0,63	5,56	4,7 %	61,2 %	12,0 %	15,6 %	11,3 %
Norway Spruce (MT)	Sawlog	3,40	0,68	0,88	0,59	5,55	4,5 %	61,3 %	12,2 %	15,9 %	10,7 %
Norway Spruce (MT)	*Baseline*	*3,12*	*0,68*	*0,88*	*0,63*	*5,31*	*0,0 %*	*58,7 %*	*12,7 %*	*16,6 %*	*12,0 %*
Norway Spruce (MT)	Energy	3,12	0,68	0,92	0,59	5,31	-0,1 %	58,8 %	12,8 %	17,3 %	11,2 %
Norway Spruce (MT)	Tapio	2,71	0,59	0,77	0,55	4,62	-13,0 %	58,7 %	12,7 %	16,6 %	12,0 %
Norway Spruce (OMT)	*Baseline*	*5,52*	*1,04*	*1,51*	*0,97*	*9,05*	*0,0 %*	*61,0 %*	*11,5 %*	*16,7 %*	*10,8 %*
Norway Spruce (OMT)	Energy	5,52	1,04	1,70	0,76	9,02	-0,3 %	61,2 %	11,5 %	18,8 %	8,4 %
Norway Spruce (OMT)	RPD	5,63	0,99	1,44	0,93	9,00	-0,5 %	62,6 %	11,0 %	16,0 %	10,3 %
Norway Spruce (OMT)	Sawlog	5,63	1,04	1,51	0,76	8,95	-1,1 %	63,0 %	11,6 %	16,9 %	8,5 %
Norway Spruce (OMT)	Tapio	4,68	0,88	1,28	0,82	7,67	-15,3 %	61,0 %	11,5 %	16,7 %	10,8 %

7.2 Previous studies

The long-term equilibrium steady-state represents a theoretical sustainable state with no changes in the inventory; the amount of wood-based products in use stays constant over time, as the supply equals the decay, while the forest growth similarly remains stable. The steady-state methodology was previously used by Pingoud et al. (2010) to study the climatic impacts of elongated rotation periods, increased average basal area and the sawlog supply. Given the different approach and the goals, a direct comparison is difficult. For the same reason, it is not sensible to directly compare the results to any other previous study either, as the methodologies and the goals are even more diverged. Regardless, a review in the magnitudes, and more importantly to what the results imply for forestry and wood-based products, gives insight and reveals some similarities between the results of the studies and the conclusions thereof.

Elongated rotations periods are generally considered beneficial for the carbon balance. For instance Liski et al. (2001) and Kaipainen et al. (2004) assert that lengthened rotations will positively affect the overall carbon balance. Results from Pingoud et al. (2010) indicate that elongating the rotation period could have a positive impact on both the carbon pools (forest and product pools) and the avoided emissions from wood-use, thus presenting a win-win scenario. Their study considered wood used in construction and energy, while treating pulpwood (for paper) similarly to energy wood. They found that lengthening the rotation period from the currently recommended, and increasing the average basal area of the forest, lead to higher production and supply of sawlogs. This led to larger carbon pools and a higher level of avoided emissions, as fossil energy intensive materials were increasingly substituted by sawnwood. The same basic idea was explored in the reduced pulpwood demand and sawlog scenarios of this study, which effectively increased the sawlog supply, while reducing the pulpwood supply. The set-up intended to reveal what the impacts of the current fibre production are. When the price of pulpwood decreased, the economically optimal rotation periods were elongated, by approximately four years, and the relative share of sawlog supply increased by 3 – 5 percentage points. This resulted in higher carbon pools, and the overall impact on the carbon balance was positive on all the stands.

Kaipainen et al. (2004) found that elongated rotations sometimes caused the harvesting potential to decrease. This results when the new rotation exceeds the maximum yield rotation. The effects from the decreased wood supply were however compensated by the increased forest carbon pools, and the overall impact was positive. Similar reaction to wood supply was observed in this study, when the forest management changed and the rotations were slightly elongated, as a result of a demand shift away from fibre-based packaging. On two of the stands, the total harvesting potential was slightly decreased from the baseline, but the increased carbon pools compensated for the loss. The use of sawnwood in construction and in other long-lived products has great potential for climate change mitigation because of its low energy intensity and long lifecycle (Sathre and O’Connor 2008, Reid et al. 2004). The average basal area and the relative share of sawlogs will generally increase with the forest age. If a shift in demand results in changes to the forest management, as observed in this study, and the increased sawlogs supply is able to compensate for the lost pulpwood, the impact on the carbon balance will be positive.

The carbon pools will increase hand-to-hand with the avoided emissions, as long as the increased sawlog production is able to off-set the lost pulpwood.

The silvicultural guidelines developed by the Forestry Development Centre Tapio are the current basis for forest management in Finland. The guidelines take into account many different economical, ecological and social considerations. What this means purely from the climatic point of view is that the guidelines are not optimal for mitigating climate change. Meanwhile the economically optimal management practices maximize the bareland value of the forest, without considering other than economic factors. This tends to increase and drive the mean annual increment (MAI) closer to its culmination point, increasing the mean annual growth, the wood yields and the climatic benefits thereof. For instance Nerg (2009) noted that with rotation lengths approximately 10 – 20 years longer than those recommended by Tapio, the annual carbon sequestration rates were higher. Similarly, Pingoud et al. (2010) show that elongating the rotations from the currently recommended could increase both the carbon pools, as well as avoided emissions from wood use.

Kujanpää et al. (2009) notes that an important factor to consider is the time horizon, with which any climatic problem is approached, as to prevent the global warming rapid action has to be taken within the next 20 – 50 years. They also outline and discuss three different generic approaches to carbon footprinting, an important tool in quantifying the carbon impacts. In the carbon uptake approach, only the biogenic carbon that is bound to the harvested wood product is taken in to consideration. All the carbon is eventually released back to the atmosphere at the end of the product lifecycle. In the lost carbon stock approach, the carbon which is removed from the forest is calculated as an emission. It takes in to account the lost carbon sequestration potential in the forest due to harvesting, which is then allocated to the product, based on the amount of wood raw material used by the application. Due to the methodology, the lost carbon stock approach favours products made from recycled fibre, as the lost sequestration potential is less significant when non-virgin fibres are used. The net carbon sequestration approach is based on the underlying idea of net forest growth due to sustainable forest management. The proponents argue that the use of wood raw material contributes to the markets, which in turn stimulates the sustainable forest management. The model allocates a portion of the annual net forest growth to the forest products, therefore reducing the forest product carbon footprint.

Eriksson et al. (2010) emphasize the need for active forest management, due to managed forests removing carbon from the atmosphere much faster than unmanaged forests. They assert that it is possible to keep a high forest carbon stock, while at the same time carry out sustainable harvests. The more difficult question is if and how to link sustainable forest management and carbon sequestration to consumer demand, which would justify including the carbon sequestration to the carbon footprint, as discussed earlier. The argument is that on certain areas, such as in the Northern Europe, the purchase of timber by the industry contributes to the application of efficient forest management practices, which then in turn ensure the high growth rate and large and increasing carbon stocks. According to the proponents, the main driver for sustainable forest management is the economic return from the forest. The link they propose follows the principle idea that reduced demand causes reduced production, which reduces harvests and the timber prices, postponing forest operations and thus decreasing the carbon sequestration rates. The study shows that in comparison to a theoretical reference scenario of an old non-managed forest, the carbon sequestration in the managed forests is indeed higher. However, the causality between the consumer demand and the net growth of forest biomass still remains hazy, and what would happen if no consumer demand existed is difficult to say. Furthermore, the question how the net carbon sequestration should be credited for wood demand is not straight forward, in case the wood harvests would completely cease. The net carbon sequestration would still continue for several decades at a significant rate, and therefore one might argue only the difference between the current situation and the no-harvest scenario hereon, should be used as a credit for wood demand.

The forest industry as a whole is in a unique position because biomass in the future will be in increasingly high demand by also the energy sector (Laurijssen et al. 2009). This opens the questions whether or not wood raw material, namely pulpwood, will be available for all the interested parties that utilize it in their operations. Already in Sweden there have been instances when pulpwood has been more valuable as bioenergy, rather than feedstock biomass for the forest industry.

The Swedish Forest Owners Association (Mellanskog) president Lars Gabrielsson has stated that it is simply the price of energy resources that determines the end-use of pulpwood and whether it is burned for energy or not (Timber Community 2010). The Forestry Centre (Metsäkeskus) has similarly noted that the improved price of energy wood is making it increasingly competitive against pulpwood in Finland as well (Metsäkeskus 2010). One might question the forest owners' willingness to harvest pulpwood for energy purposes, but according to a recent survey, two-thirds of Finnish forest owners had no objections to energy harvests from pulpwood (Karttunen et al. 2010). Hetemäki and Hänninen (2009) similarly assert that from the economic or environmental point of view, there is no reason to limit pulpwood outside of the energy use.

7.3 Reliability of the results

The reliability of the results is affected by a number of factors, such as the wood and biomass yields obtained from MOTTI, and the parameters and assumptions taken in calculating the carbon pools and avoided emissions.

To begin with, the study relies on the forest growth simulations carried out on MOTTI software. According to Hynynen et al. (2005), the growth and the wood yield components of MOTTI are the most reliable individual components in the software, whereas the biomass model is more tentative. They further note that MOTTI is not able to account for certain risks in forestry, such as damage from insects, forest fires, wind and other similar natural occurrences. Regardless of some of MOTTI's short-comings or rather simplifications, it is a valuable tool suitable for this kind of research. The modeling data in MOTTI includes sample plots from some 4400 sites, and over 68000 trees from throughout Finland. MOTTI is based on the newest available empirical growth models and it is accurate and specific in regards to the tree species, the geographical location, and the forest site type of the stand.

After the stand simulations, the results become dependent on secondary data, as the wood yields from the simulations, are converted to the climatic indicators used in the study; carbon pools and avoided emissions. All the assumptions taken, as described in the methodology chapter, should be therefore naturally considered when interpreting the results. Necessary simplifications were taken and for instance carbon at landfills and carbon in the soil were not included. In the context of this study, the inclusion of carbon at landfills would likely not had a considerable impact, because of the high recycling rate in Finland, whereas soil carbon might have had a more significant impact. There are large uncertainties related to soil and litter carbon, which is the reason why they were not considered, as the results would have been much more unreliable than those related to the forest and product carbon pools.

The forest carbon pools were obtained by converting the average stand biomass from MOTTI to carbon by a factor of 0.5, and further to carbon dioxide by a factor of 44/12 (~3.67), both of which are widely used in other studies. In reality the amount of carbon in wood slightly differs between tree species. The product carbon pools were obtained similarly by converting the wood yields to carbon and carbon dioxide, but in addition the wood yields had to be converted to mass units. This was done by a factor of 0.4 (400kg/m^3), which is a reasonable assumption for the softwood density of Norway Spruce and Scots Pine, and earlier used for instance by Pingoud et al. (2010).

Obtaining and choosing the displacement factors used for the avoided emissions was slightly more problematic than other factors used in the study. The displacement factors are fairly simple to calculate for specific and individual functions or products, but much more difficult for larger product groups or materials; they are highly sensitive to the application of the product and material. A large amount of studies on wood used in construction exists, and therefore the displacement factor for sawnwood was also fairly simple to obtain. Based on a literature review of wood construction studies, Sathre and O’Connor (2008) concluded that a displacement factor of 2.0 could be viewed as reasonable middle estimate for an end-product sawnwood displacement factor. Therefore the displacement factor of 2.0, relative to product carbon (as opposed to raw material carbon), is applied in this study. They also discuss the energy use and note that typically the displacement factors suggested for energy wood range between 0.5 and 1. Pingoud et al. (2010) use a displacement factor of 0.89 for pulpwood and energy wood. The biggest problem with pulpwood is finding realistic substitutes for paper. Conventional printed media can be substituted by for instance electronic paper, but the possible scenarios are very case-dependant.

No previous studies on displacement factors for fibre-based packaging materials exist as of to date. It is simple to calculate a single product specific displacement factor based on the lifecycle studies. However, a displacement factor for the fibre-based packaging materials as a whole was impossible to obtain in the scope of this study. Based on the literature analysis in chapter 4, it is reasonable to assume that fibre-based packaging as a whole has a positive impact on the climate when substituting alternative materials. Further, a sensitivity analysis was conducted to see at which point, and from how far from the assumed factor of 1.5, the substitution is no longer beneficial to the environment. For the most parts, the sensitivity analysis only changed the magnitude of the results.

Finally, the financial performance of forestry should be considered, as the alternative management regimes are based on economically optimal forest management. The price data and the interest rate used in the optimization affect the results as they are the basis for the simulations in MOTTI. Considering the price of pulpwood, it would not seem very realistic to assume a steeper price drop than the 10 € applied. On the contrary, the increased demand for energy wood in the future could increase the price of pulpwood. In this study however, it was more interesting to examine what kind of effects the decreased supply would have. Furthermore a very low price of pulpwood (nearing zero) decreases the reliability of the optimization. The interest rate of 3 % is often applied, and it can be considered a reasonable for this kind of investments. A higher interest rate would imply a higher risk or the availability of better alternative investment opportunities. This decreases the present value of the future cash flows, and therefore would likely shorten the rotation periods. This in turn would decrease the gap between Tapio management and the economically optimal management regimes.

8 CONCLUSIONS AND DEMAND FOR FURTHER RESEARCH

Packaging materials are carbon storages

While not as significant carbon storages as sawnwood or other long-lived products, packaging materials as well as pulpwood products in general, should be taken in to consideration as effective carbon sinks. Packaging materials clearly contribute to the carbon pools and delay the re-emission of carbon to the atmosphere. The results showed that contribution from pulpwood products ranged between 2 – 4 % of the total product pools. In absolute terms, per cubic meter of harvested wood used, mechanical pulp binds almost twice as much carbon as sawnwood or chemical pulp. As some 0.26 Tg of fibre-based packaging materials are annually consumed in Finland, the total amount of biogenic carbon bound to the consumed fibre-based packaging materials is roughly 0.5 $TgCO_2$. How much of this is bound to the materials at any given moment, or how much it delays the re-emission of carbon to the atmosphere on a national scale, is uncertain.

Fibre-based packaging materials help to avoid greenhouse gas emissions

It is clear that wood, or any other single material to that fact, is not unilaterally always the best option for packaging. Regardless, it is reasonable to assume, that the overall impact of using fibre-based packaging materials, from sustainably managed forests, is beneficial to the environment. Furthermore, it also appears the climatic benefits from fibre-based packaging materials (through substitution of alternative materials) used in primary and secondary packaging, are relatively higher than those of fibre-based materials used for tertiary packaging functions. The reasons for this could be logistical and geographical, but to ensure the best possible courses of action in packaging and logistics, this certainly calls for further research in the future.

Increasing material recycling and reuse is highly preferable

Increased recycling and reuse is highly preferable as recycling and reuse effectively lower the product carbon footprint and delay the re-emission of biogenic carbon to the atmosphere, by elongating the lifespan of fibres and the carbon bound therein. The end-of-life management of wood products has a high impact on the product's climate friendliness. Reusable and durable products, and products made from recycled non-virgin fibres, have much lower impact on the environment than products that are not reused, have a short lifecycle and are not recycled.

Forests should managed and used for raw material rather than left unattended

Managing forests resources sustainably and using forest products in a responsible manner is a climate change mitigation strategy that enables lowering the amount of carbon in the atmosphere with relative ease, compared to many other mitigation strategies. The results from this and previous studies support the notion that actively managed forests have higher climatic benefits than leaving the forests unmanaged. Furthermore, responsible use of forest resources for raw materials and manufacturing of forest products enables substituting other more energy intensive materials, thus lowering the carbon emissions at the source.

Economically optimal management practices are climatically preferable to Tapio

Based on the results, economically optimal forest management regimes yield more wood annually and have higher climatic benefits than managing the forests according to the recommended current practices by the Forestry Development Centre Tapio. The economically optimal management regimes showed clearly higher climate change mitigation potential than the regimes following the guidelines. In fact, managing the stands according to the silvicultural guidelines provided the least climatic benefits out of all scenarios. This is interesting and worth noting, as the guidelines are the current basis for the management practices in Finland.

Possibility for win-win scenarios

The results indicate the possibility that win-win scenarios exist by shifting production from pulpwood to sawlogs; on some of the stands in the RPD and sawlog scenarios, both carbon pools and avoided emissions increased from the baseline simultaneously. Additionally, the results showed that a change from the current recommended forest management practices in Finland also yield higher associated climatic benefits in relation to the carbon pools and avoided emissions. This supports the notion that the generic mitigation strategies are not necessarily mutually exclusive as it is possible to simultaneously utilize sequestration and substitution strategies, in which both the carbon pools and the avoided emissions are increased.

Use of virgin fibre for energy purposes over forest products should be avoided

In the future the share of renewable energy will all but certainly increase. In Finland and the European Union this is guaranteed by the European Union RES-directive which mandates the renewable energy targets for all the Member States. In Finland the share of renewables is set at 38 %, or in terms of primary energy, approximately 39 TWh (Finnish Forest Research Institute 2010). About half of this is expected to come through the increased use of wood chips. From the environment point of view, it is critical to ensure the wood raw material availability for the forest industry and the manufacturing of forest products, if pulpwood is increasingly used as bioenergy rather than feedstock biomass for the forest industry. The shift from packaging material to energy use can adversely affect the carbon pools and the avoided emissions. The use of virgin fibres for energy purposes, rather than feedstock biomass for the forest industry, should be critically considered if optional to each other. Only cellulose fibres no longer viable for use in the manufacturing process should be condemned to the final use recycling options, such as incineration with energy recovery. It is important to remember however, that both energy and fibre-based packaging are beneficial in their own applications. If there is an abundance of wood raw material available, then the increased use of wood energy is a win-win, as emissions can be avoided in both the applications simultaneously with no adverse impacts due to scarce resources whatsoever.

Further research on alternative packaging materials is necessary

In the future it would be highly desirable and interesting to examine different transport packaging systems, namely corrugated boxes and reusable plastic containers, closer to the Finnish context. The average transport distances, manufacturing of materials, recycling, energy systems and the logistical infrastructure in general, vary considerably between nations and geographic locations. Few publicly available scientific papers on the subject exist, despite the importance, even internationally. The Paper and Paperboard Packaging Environmental Council (PPEC 2011) understandably asserts that in environmental terms, there’s no clear winner in which packaging system is better. The Confederation of European Paper Industries (CEPI 2011) even goes as far as to say the corrugated board packaging is in fact the better option. In support of their argument, the plastic industry on the other hand gladly cites Singh et al. (2006), one of the few studies, if not the only comparative study on corrugated board and reusable plastic containers by the scientific community to date.

Unified carbon footprint methodology is needed

The carbon footprint of wood-based products has been extensively studied in recent years, by both the industry and the scientific community. No unified methodology for assessing the product carbon footprint exists as of yet. While in principle the same, the methodologies for calculating the footprints differ in, for instance, how the biogenic carbon in the growing forest stock is accounted for, or rather if it is accounted for at all. The inclusion of biogenic carbon sequestration in managed forests would show very beneficial for the wood products, as it would in many cases offset a large portion of the total wood product carbon footprint. For clarity and a multitude of other reasons, it is important that a unified methodology can be found and agreed upon, in the near future.

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