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Carbon Reservoirs in Wood Products-in-Use in Finland: Current Sinks and Scenarios until 2050

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This study addresses the question of how much carbon will be sequestered in wood products during the coming decades in Finland. Using sawnwood and other wood material consumption data since the 1950s and inventory data of carbon reservoirs of wood products in the Finnish construction and civil engineering sector, we first derive estimates for the carbon reservoirs in wood products-in-use in that sector. We then extend the estimate to include all wood products-in-use. We find that the carbon pool of wood products in the Finnish construction and civil engineering sector grew by about 12% since an inventory for 2000, and that the overall estimate for carbon reservoirs of Finnish wood products in 2004 was 26.6 million tons of carbon. In building the scenarios until 2050, econometric time series models accounting for the relationship between wood material consumption and the development of GDP were used. The results indicate that the range of carbon reservoirs of wood products in Finland will be 39.6–64.2 million tons of carbon in the year 2050. The impacts of different forms of the decay function on the time-path of a carbon sink and its value in wood products were also studied. When a logistic decay pattern is used, the discounted value of the predicted carbon sink of wood products in Finland is between €850 and €1380 million – at the price level of €15/CO_2 ton – as opposed to 440–900 million euros, if a geometric decay pattern is used.

Keywords climate change, carbon pool, wood products, present value, decay function
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1 Introduction

Increases in CO_2 emissions can be offset, to an extent, by accumulation in carbon sinks, such as forests and other plant biomass. It has also been recognized that wooden materials and structures (harvested wood products) are an important pool of carbon and that they may constitute a carbon sink (see e.g. Brown 1998, IPCC 2006, IPCC 2007). In the Kyoto protocol (United Nations 1998) carbon sequestration of wood products is not included as a possible tool for countries to use in meeting their CO_2 emission targets. This is in contrast to carbon sinks in forests, which are included in Article 3.4 of the agreement. However, in the IPCC (2007) report, carbon sequestration in wooden materials is recognized as a possible means for mitigating climate change pressures. Furthermore, in Finland, carbon reservoirs of wood products-in-use have been included in the national greenhouse gas inventory (Greenhouse gas emissions 2007).

In this study we are interested in evaluating the current and future carbon reservoirs in wood products in Finland. The climatic role of wood-based products manufactured in Finland (and possibly exported to other countries) has been addressed by Karjalainen et al. 1994 and Karjalainen et al. 1995. An inventory-based study of the carbon pools of wood-based products in the Finnish construction and civil engineering sector estimated that the annual increase in carbon pools in the wood products in the sector between the years 1995–2000 was 0.3 Mt (1.1 Mt CO_2 ekv/year (Pingoud et al. 2003). Other national-level studies on the carbon pools in wood-based products are, e.g., EPA (2007) for the USA, Briceno-Elizondo and Lexer (2004) for Austria, and Apps et al. (1999) for Canada. Furthermore, Skog and Nicholson (1998) presented methodology to calculate carbon sequestration in both forests and harvested wood products in the USA.

Our focus in this study is on the wood products-in-use processed in the Finnish mechanical wood-working industry and consumed in Finland. Finland is an interesting case because of its high wood-product intensity in the economy, and because the consumption of wood products (mainly based on sawnwood) has increased rapidly during the past few years, especially since 1995. This suggests that the annual carbon sinks of the wood products have increased since that time. We will estimate these sinks, and utilizing rigorous econometric time-series analysis, we will form scenarios of carbon pools in the wood products in Finland up to the year 2050. Carbon storages of wood products in landfills, or the substitution effects of using wood material to replace fossil fuels or materials that are more fossil energy intensive, are not taken into account in our analysis. The EPA (2007) study shows that in the United States the carbon storages in landfills could be more than half of carbon reservoirs of products-in-use. However, due to uncertainties and lack of information in our case, we left carbon in landfills out of our analysis.

Another interesting question is what is the magnitude of the economic value of climate benefits that will be generated by the expanding carbon pools in the wood-product sector. This is also important in view of economic incentives for adopting any international programs that would reimburse countries from building up carbon pools in forest-based products. For that end, we will further calculate the present values of the carbon sinks in wood products in Finland until 2050.

To anticipate the results, the analysis carried out in this study indicates that the annual carbon sinks in wood products in Finland have grown in the last decade. The results also suggest that carbon reservoirs in wood products in Finland will continue to expand in the next few decades and thus that the wood-product sector will be an important carbon sink in Finland in the coming decades. Also, the economic value of the future carbon sinks may be substantial.

The rest of this study is organized as follows. We first illustrate the change in the consumption of the main mechanical wood products in Finland during the past decades. This is followed by estimates for the 2004 carbon reservoir in the wood products using the annual consumption figures and an inventory on the carbon reservoir in Finland in 2000. Next, we present the econometric time series analysis used as a basis of one of the carbon content scenarios until the year 2050. This scenario, which predicts a growth in the wood consumption in Finland, and two other scenarios representing a constant wood consumption and a decreasing consumption, respectively, are presented in the next section. The present value of the carbon sink patterns until 2050 are calculated in the following section using two alternative decay-function patterns. Conclusions are presented in the discussion section.

2 Development of Wood Product Consumption in Finland 1955–2005

2.1 Sawnwood Consumption

Sawnwood consumption in Finland increased slowly from 1955 to 1996 (see Fig. 1). After that, the growth became more rapid, and the consumption per capita almost doubled in just eight years. However, the growth of the consumption seems to have slowed down in the early 2000s.

The increasing sawnwood consumption reflects the growth of the building sector, as well as the growing popularity of wood as a building material in Finland. The wood intensity of the Finnish economy is reflected in the series obtained by relating the sawnwood consumption to trends in the GDP in Finland. Sawnwood consumption per GDP decreased from 1955 until the middle of the 1990s, but has grown slightly since (Fig. 2).

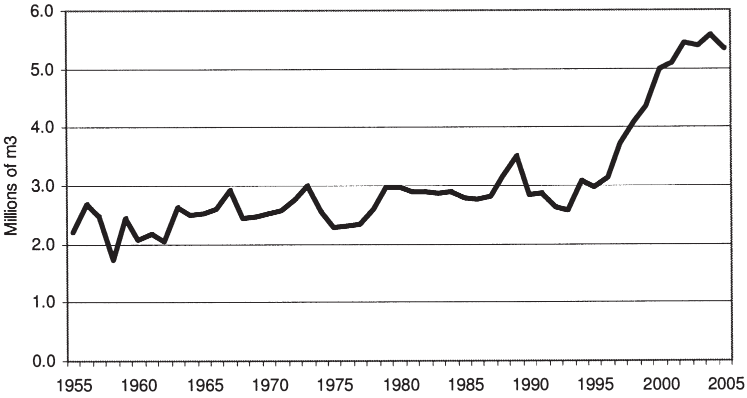

Fig. 1. Finnish sawnwood consumption 1955–2005 (Data source: Finnish Forest Research Institute 2006).

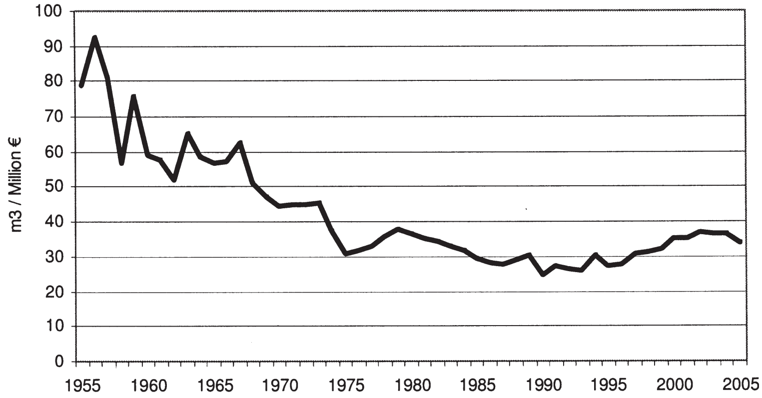

Fig. 2. Finnish sawnwood consumption per GDP 1955–2005 (Data source: ETLA 2007).

2.2 Plywood, Particle Board and Fibre Board Consumption

The consumption of wood-based panels in Finland is small relative to the sawnwood consumption. In 2005 the board consumption was 229 000 m^3 for plywood, 274 000 m^3 for particle board and 221 000 tons of fibreboard, while the consumption of sawnwood was 5.2 mill. m^3. Of the wood boards, the plywood and fibre board consumption has shown some modest increases in recent years.

3 The Carbon Pools of Wood Products in Finland in 2004

3.1 Carbon in the Finnish Construction and Civil Engineering Sector

Pingoud et al. (2003) made an inventory-based study of carbon reservoirs of wood products in the Finnish construction and civil engineering (CCE)[1] sector for the year 2000. They estimated that carbon reservoirs of wood products in that sector were 17.3 Mt, of which the share of sawnwood reservoirs was 15.65 Mt and the share of wood-based panel reservoirs was 1.68 Mt of carbon. Pingoud, Perälä and Pussinen (2001) extrapolated the Pingoud and Perälä (2000) 1995 inventory figure to obtain a carbon reservoir estimate of about 5 Mt for the year 1955. This estimate is also used in this study as an initial carbon reservoir for the year 1955 in the CCE sector in Finland. To derive the 2004 estimates for the carbon reservoirs, we then used the domestic consumption statistics from 1955 until 2004 for sawnwood and for wood-based panels.[2] Annual decay percent of the carbon content was chosen in such a way that the annual consumption figures for sawnwood and wood-based panels generated an accumulated carbon reservoir coinciding with the inventory year 2000 estimate of 17.3 Mt.

To follow the carbon content in the wood products within the CCE sector, information is needed of the shares of the total annual consumption of wood products that actually are used within that sector. For these shares, we applied 75% in the case of sawnwood, 20% in the case of plywood, 50% in the case of particle board, and 70% in the case of fibre board (VTT/Woodfocus 2001). These shares were assumed constant over the study period.

We first used the geometric decay percent to estimate the amount of carbon released from the wood products annually[3]. However, for the consumption year the decay percent was taken to be a given construction loss parameter, for sawnwood, 5%, for plywood, 94%, for particle board, 38% and for fibre board, 10%, which consists of wood materials used in the construction process and wastages (Pingoud and Perälä 2000). Then, for example, as 75% of the annual consumption of sawnwood has been used in the CCE sector and 5% percent is the construction loss, then after the first year, $(0.75*0.95)=71.25\%$ of the original domestic consumption remains in the products within the sector to the second year. Subsequently, starting from the second year after the initial use, the sawnwood decay percent is assumed to be constant annually. Furthermore, the initial carbon stock and the annually consumed sawnwood were assumed to have the same decay percent. For the wood-based panels, the first-year decay, and the subsequent decay pattern were derived in an analogous way, and similar assumptions were used.

The procedure described above gave estimates for the annual levels of the carbon stock in the Finnish CCE sector for the period 1955–2005. These estimates were in line with the existing available estimates for the period prior to 2000 (Pingoud et al. 2003), and for the period 2000–2004 the annual carbon sinks in the CCE sector was estimated to be 0.52 Mt. The estimate for the carbon stock in the Finnish CCE sector for the year 2004 was 19.4 Mt. Of this, sawnwood reservoirs accounted for 17.6 Mt and wood-based panel reservoirs for 1.80 Mt.

3.2 Carbon in All Wood Products in Finland

To derive estimates for the total carbon content in all wood products in Finland, one needs to account for wood material used outside the CCE sector. These other uses for wood material consist of, e.g., furniture and packaging material. As the share of all consumed sawnwood used within the

Table 1. Carbon content in wood products in Finland in 2000 and 2004.

	2000 (Mt C)	2004 (Mt C)	Growth
Sawnwood products	20.87	23.51	13%
Wood-based panel products	2.86	3.05	6%
Plywood products	0.044	0.050	15%
Particle board products	1.51	1.55	2%
Fibre board products	1.31	1.45	11%
All wood products	23.73	26.55	12%

CCE sector was 75%, this leaves a 25% share for the other uses. Similarly for plywood, particle board, and fibre board, these shares were 80%, 50% and 30%, respectively. We used these shares and assumed that the decay pattern within the other sectors were similar to those in the CCE sector to derive the total carbon content figures for the period 1955–2004. Table 1 shows the results for the year 2000 (the inventory year) and for the year 2004.

For the year 2004 we estimated that the total carbon content in all wood products in Finland was 26.6 Mt of carbon. (For comparison, trees in forests in Finland contain about 800 Mt of carbon (Liski et al. 2006)). Of this, sawnwood accounted for 23.51 Mt, and wood-based panel reservoirs accounted for 3.05 Mt. It is noteworthy that according to the present results the overall carbon reservoirs in wood products have grown by 12% during the present decade, with an average annual carbon sink of about 0.7 Mt. For comparison, this was about 3% of total annual greenhouse gas emissions in Finland during the period (Greenhouse gas emissions 2007).

4 Carbon Reservoir Scenarios for 2005–2050

4.1 Econometric Forecasts

We will present three scenarios for the carbon reservoirs of wood products in Finland for the years 2005–2050. To form one of these scenarios, growth figures for sawnwood and wood-based panel consumptions in the period of 2005–2050 were derived using econometric time series models. Economic activity, reflected in the GDP, is the main driver of wood-product consumption in Finland. Our model specifications were such that the consumption series were regressed on their own past values, and the gross domestic product (GDP) figures. In this section the tests of the stochastic structure of the series are first presented, followed by the presentation of the models and the consumption forecasts for sawnwood and the wood boards. The carbon reservoir scenarios are presented in the next section.

4.1.1 Data and Stochastic Structure of the Time Series

All the time series used in this study were yearly data. The sawnwood consumption series is from the Finnish Statistical Yearbook of Forestry 2006, while the values for the plywood, particle board and fibre board series are apparent consumptions, calculated from the production, export and import data obtained from the FAO data base (Finnish Forest Research Institute 2006, FAOSTAT database 2007). The Finnish gross domestic product (GDP) series was collected from the online database of the Research Institute of the Finnish Economy (ETLA database 2007), and it was deflated into the prices of 2005. The sawnwood series covers the period of 1955–2004 and the other three consumption series the period of 1961–2004.

Diebold and Kilian (2000) studied the impact of the stochastic structure of univariate time series on the forecasting of the series. They concluded that difference and trend stationary models4 may lead to very different forecasts, and that the unit root tests can be used as a formal criterion for choosing between these two structures.[5] They also found out that pre-testing for the unit roots improved the forecasts. Christopherson and Diebold (1998) studied the multivariate models and concluded that for forecasting purposes, it is more important to apply the right degree of integration than it is to impose the right form of cointegration restrictions. In this analysis we will first use the unit root test to determine the stochastic structure of each series, and then identify and estimate the time series models. The final forecasts are calculated by combining single-model forecasts.

The augmented Dickey-Fuller (ADF) unit root test was applied to both the levels and differences of the series in order to decide whether we should treat the series as stationary or non-stationary. The results are presented in Appendix 2. The optimal lag length for each test was selected using the Schwarz criterion. The autocorrelations of the series do not show persistent time dependence, but the ADF test results clearly point to a non-stationary process in each case.

4.1.2 Econometric Models and Specifications

We applied two basic time series model families: The univariate Autoregressive integrated moving average (ARIMA) model and the multivariate Vector autoregressive (VAR) model.

Differencing once removed all the autocorrelation from the series, so that more complicated ARMA specifications were not necessary and thus the only useful ARIMA specification was a random walk with a drift (RWD):

$$y_t = \alpha + y_{t-1} + \varepsilon_t \tag{1}$$

where y_t is the value of a series at time t, α is a constant intercept, and ε_t is an error process, that is assumed to be white noise with a zero mean and a constant variance. The intercept (the drift term) α is here more powerful than what it would be in an ordinary regression model, because it now creates a linear trend term $t\alpha$ into the forecast series.[6]

The VAR model specifications included the standard VAR model, the VARX model, with GDP set exogenous[7] and the Vector error correction (VECM) model with cointegration restriction and error correction terms. As all the unit root tests pointed to non-stationarity of the series, the input series were differenced before the identification of the standard VAR models and the VARX models. The lag length of a VAR model can be determined either by sequential testing[8] or by using a model selection procedure with a chosen information criterion[9] (Lütkepohl 2004). We applied the latter approach and estimated each VAR model with all the possible lag length combinations up to 5 lags[10], and then chose the specification that minimized the value of the Schwarz criterion (see Appendix 3 for the selected lag lengths).

4.1.3 Forecast Calculations

As the underlying statistical process of the time series is usually unknown, the final forecasts can sometimes be made more robust by calculating combinations of single model forecasts. In the simplest case this combination would be an average of selected forecasts[11], so that an equal weight would be given to each single forecast value. However, the median forecast can perform better in situations where some forecasts could have an excessive effect on the combination (Hendry and Clements 2002). Because of the long forecast time span (2005–2050), we decided to use the median of the single model forecasts:

$$y_t^{MF} = \text{median}(y_{1t}^F, y_{2t}^F, \ldots, y_{st}^F;\ t = 2005, \ldots,\ 2050 \tag{2}$$

where s is the number of the models. In the present case this was the median of VAR, VARX, VECM and RWD model forecasts. The growth rates of the resulting forecast combinations are listed in Table 2. Due to the structures of the series and the different sample sizes, the estimation periods varied, too.

Table 2. Growth rates of the forecast combinations.

Series	Estimation sample	Volume 2004 (1000 units)	Volume 2050 (1000 units)	Annual growth rate	Total growth
Sawnwood	1956–2004	5575	10135	+1.31%	+81.80%
Plywood	1962–2004	191	336	+1.23%	+75.60%
Particle board	1971–2004	259	27	–4.79%	–89.55%
Fibre board	1962–2004	215	379	+1.24%	+76.39%

4.2 Three Scenarios for Carbon Reservoirs in Wood Products 2005–2050 in Finland

The estimated annual growth rates (Table 2) for the consumption of sawnwood, plywood, particle board and fibreboard, were used together with the assumed decay rate as explained in Section 3, to form *scenario 1* for the carbon reservoirs of sawnwood products for 2005–2050. Because of the dominant role of sawnwood use in the overall wood-product consumption in Finland, it is evident that the selected growth rates of the sawnwood consumption dominate the overall outcome of the carbon storage size in all wood products. We therefore varied the growth figures of sawnwood consumption to derive the two other scenarios, while maintaining the wood panel consumption rates as indicated by the econometric analysis. In *scenario 2* the consumption of sawnwood was set at the level of their respective consumption in the year 2004. Thus, this scenario represents the status-quo scenario in terms of the sawnwood consumption. For *scenario 3* we used the negative of the growth figures estimated for sawnwood in scenario 1. This scenario thus represents an overall decreasing consumption of sawnwood products, the annual percentage of the decrease being 1.31.

The derived carbon storage sizes for the year 2050 in the three scenarios are presented in Table 3. The 1.31% growth rate for the annual domestic sawnwood consumption leads to 59.7 Mt carbon reservoirs of the sawnwood products by 2050. This is 153% above the 2004 stock. The estimate for carbon stock in sawnwood products for the year 2050 with constant consumption is 44.8 Mt of carbon. This represents a 91% increase from the year 2004 level. Finally, the scenario according to which sawnwood consumption would annually decrease by 1.31%, gives a carbon stock of 35.0 Mt of the sawnwood products in Finland by 2015, representing a 49% increase from the 2004 level. The wood-based panels consumption forecast for the years 2005–2050 estimates that the carbon reservoirs in those products together by 2050 are 4.6 Mt of carbon, a 50% increase from the 2004 level.

The predicted total carbon reservoirs in the wood products in Finland for the year 2050 range between 39.6 and 64.2 Mt of carbon in the three scenarios (Table 3). It is noteworthy that all the scenarios predict a significant growth for the carbon content until the year 2050. Even in the scenario in which the annual consumption of sawnwood is predicted to decrease by 1.31%, the carbon reservoirs of wood products in Finland are 49% above the 2004 level. This apparent carbon sink is due to the very strong increase in the consumption of sawnwood in Finland in the 1990s and early 2000s. This increase will, in fact, force the carbon reservoirs to increase in the future as well, even if the annual consumption levels of wood products will be declining moderately.

Fig. 3 presents the trends in carbon reservoirs in wood products in Finland since 1955, and in the three scenarios for 2005–2050.

In the beginning of the 1990s the growth of carbon stock seems to have been slightly slowing; this happened because the sawnwood consumption declined at that time due to the economic recession. In the late 1990s the growth increased, due to an increase in the sawnwood consump-

Table 3. Carbon reservoir scenarios of wood products in Finland.

	2004	2050		
		Scenario1	Scenario 2 (Mt C)	Scenario 3
Sawnwood products	23.51	59.67	44.79	35.00
Wood-based panels products	3.05	4.57	4.57	4.57
Plywood products	0.05	0.12	0.12	0.12
Particle board products	1.55	0.80	0.80	0.80
Fibre board products	1.45	3.65	3.65	3.65
All wood products (Growth)	26.55	64.24 (+142%)	49.36 (+86%)	39.57 (+49%)

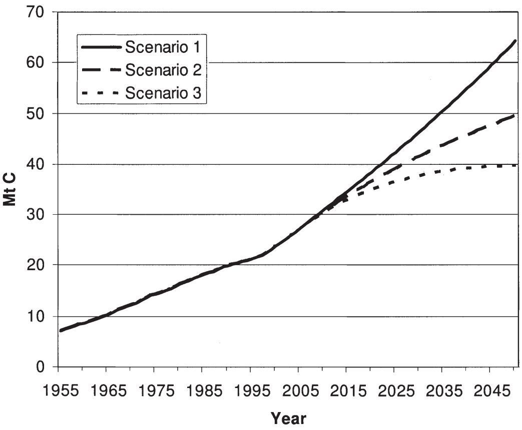

Fig. 3. The carbon reservoirs of wood products in Finland since 1955 and in three scenarios for 2005–2050.

tion. Naturally, scenario 1 gives the maximum estimate for carbon reservoirs in Finland between the years 2005 and 2050. In that scenario, the reservoir increases are escalating over the period. In scenario 2 the carbon reservoir is growing, but the growth is slowing down. The steady state for scenario 2 (zero-growth scenario) for the sawntimber carbon stock would be about 62 Mt of carbon; about one half of the growth after 2004 will take place before 2050. Also, in scenario 3 with the 1.3% annual decrease in the domestic sawnwood consumption, the carbon reservoir in sawnwood products increases until 2050. In that scenario the annual sawnwood consumption would be 3.0 mill. m^3 in the year 2050, which is only a little over one half of the current consumption levels.

To shed light on the sensitivity of the results with respect to the assumptions used, we carried out the calculations with both a 10% increase and a 10% decrease in the values used[12] , and ran the analysis again to match it to the inventory results for the year 2000, using initial carbon stock for the year 1955 as before. The results of this sensitivity analysis are presented in Appendix 4. The outcome of the sensitivity analysis indicates that the results are most sensitive to the assumptions related to the share of the CCE sector of the total wood consumption. The sensitivity analysis was done also for wood-based panels. These results, which are not reported here, followed the sensitivity results for the sawnwood products.

In the above scenarios the foreign trade of wood products is not taken into account. Thus, the analysis based on domestic consumption of wood products ignores the effects of indirect foreign trade due to exports and imports of finished products using the consumed wood products. Thus, if exports (imports) of finished products exceeds imports (exports) the estimates are biased upwards (downwards). In Appendix 5, sensitivity analysis results are presented that aim at showing the effects of net exports on the scenarios.[13] The analysis, including net export of wood product, gives a lower decay percent to the domestic sawnwood reservoirs because the export has been positive and growing in the late 1990s. After the year 2000 the imports of wood houses and furniture have been growing while the export has been stable, leading to a decreasing net exports of wood products. The scenario estimates for the year 2050, taking into account the effects of foreign trade vary from the original ones between –4% and 1%.

In the study the decay percent in the CCE sector is estimated using inventory estimates of carbon stock in that sector. However, there is no such inventory estimates of the carbon stock of wood products in other sectors. In Appendix 5 scenario estimates are also presented for the year 2050 where the decay percent in the non-CCE sectors is assumed to be twice that compared to the decay in the CCE sector. This decreases the estimates of carbon reservoirs in the non-CCE sector by about 30% percent in 2004, and the total carbon reservoirs will decrease by about 10%. The decrease in the estimated carbon reservoirs in 2050 in the non-CCE sector was between 36% and 45% and in the total carbon reservoirs of sawnwood between 9% and 11% depending on the scenario and the assumed initial carbon stock in the non-CCE sector in 1955.

The sensitivity analysis shows that there is a need for better information on the consumption and use of wood products, especially in the non-CCE sector, but those results support the conclusion that the carbon reservoirs will be growing in all scenarios between the years 2004 and 2050.

5 The Present Value of the Estimated Growth of Carbon Storages in Wood Products

It is the volume of future carbon sinks in wood products that could serve as a basis in international compensatory programs, where a country could be reimbursed for accumulating carbon sinks in wood products.[14] From that point of view, it is therefore interesting to calculate the value of national carbon sinks in wood products. In this section, we calculate this value for the three scenarios of wood product accumulation in Finland. The present values are calculated based on the values of the emissions offset by the carbon sinks in the different scenarios.

Because the assumed decay pattern of carbon release is an important factor in determining the future accumulation of carbon reservoirs (IPCC 2006, IPCC 2007, Richard and Stokes 2004), and especially the monetary value of these reservoirs, we use two alternative decay patterns, namely a geometric one and a logistic one. The information on the actual decay process does not give an advantage to those patterns to fit the actual decay curve, but shows how the present values of those reservoirs depends on the assumed decay pattern. In the geometric pattern, the decay percentage is assumed to be constant over time, while in the logistic one the assumption is that wood products at first release carbon at a lower percentage rate, but that this rate increases towards the middle of the product life cycle, before it slows down again in the later stages of the life cycle.

The present value is calculated for the base year 2005 including all wood products. The annual geometric decay percent figures after the consumption year were the same as those used in the scenario analysis. For sawnwood this was 1.75%, and for the wood-based panels the annual decay figure was 2.89%. In the case of sawnwood, the decay percent used (1.75) means that 25% of the original carbon amount of a sawnwood product would remain after 79 years, whereas the corresponding time for the wood-panel products would be 47 years (with 2.89% annual decay). These lengths of time were used for the logistic decay functions also, to indicate the point in time when the products would have 25% of their original carbon left. Thus, the two decay functions are used in such a way that the 25% share of the original stocks coincide in time. The detailed forms of the logistic decay functions for sawnwood and wood-based panels are presented in Appendix 6.

In calculating the present value of the carbon sinks, we assumed the annual interest rate to be 4%. Furthermore, the carbon dioxide price was assumed to be constant at €15/t (corresponding to €55.6 for stored carbon ton).[15] Table 3 presents the calculated present values of carbon sinks in wood products implied by the two decay functions. The values in the table thus present values of the emissions offset by the carbon sinks in the wood products in Finland in the different scenarios.

Because the logistic decay function is at first more gently sloping than the geometric one, the carbon reservoirs stay at a higher level in the beginning than with the geometric decay function. Since discounting in general emphasizes carbon reservoirs in the short run, this reflects in the higher present values in the case of the logistic

Table 4. The effects of a decay function on the present value of carbon reservoirs in wood products in Finland in scenarios for sawnwood consumption 2005–2050.

	Decay function					
	Geometric (€ million)			Logistic (€ million)		
Scenario 1: sawnwood products	861			1292		
Scenario 2: sawnwood products		593			983	
Scenario 3: sawnwood products			402			761
Wood-based panels products	41	41	41	86	86	86
All wood products	902	634	443	1378	1069	847

decay pattern. In all scenarios the present value in the logistic decay function is about €400 million higher as compared to the values produced by the geometric function. The lower the consumption assumptions in the scenarios, the larger the relative differences between the present value of the two decay patterns. For comparison, the present values of carbon reservoirs are about 35% to 115% of yearly domestic sales of the Finnish mechanical wood-processing industry (Finnish Forest Research Institute 2006).

To see how sensitive the present values are with respect to changes in the interest rate we also calculated them with 2% and 6% market interest rates. These results are presented in Appendix 7. The changes in the interest rate affect the present value of the carbon sinks in a similar way in both of the decay functions, with almost the same percentage change. For a more general discussion of the choice of interest rate in the economic analysis of climate change, we refer to Sterner and Persson (2007).

6 Conclusions

While carbon reservoirs in wood products are not recognized in the Kyoto protocol, they are included in the 2006 IPCC national accounting guidelines (IPCC 2006, IPCC 2007). It is possible that the role of these reservoirs will be accounted for in the future climate negotiations. Carbon reservoirs of wood products consumed domestically is one possible basis for an international compensatory system, where countries could claim benefits from climate services emanating from increased carbon stocks in wood products.

In this study we addressed the question of the potential magnitude of wood-product carbon reservoirs in Finland in the future decades. Finland is an interesting case because of its high wood-product intensity in the economy, and because the consumption of wood products (mainly based on sawnwood) has increased rapidly during the past few years. The results show that the annual carbon sinks in wood products were about 0.7 Mt of C between 2000 and 2004, an increase from the level of earlier decades.

Our results indicate that the carbon reservoirs in wood products will likely be expanding in Finland in the coming decades. All of the presented wood-product consumption scenarios – even the one where the consumption of wood is predicted to decrease – showed increasing reservoirs of carbon in the wood products until 2050. In the scenario where the sawnwood consumption is assumed to stay at its current level, the carbon reservoirs of wood products in Finland would almost double from their current level by the year 2050. A scenario predicting an annual 1.3% increase in sawnwood consumption indicated that the carbon reservoirs would expand by almost 2.5 times by 2050. However, the sensitivity analysis of the study shows that better information on the consumption of wood products and foreign trade will be needed to analyze carbon reservoirs in wood products-in-use more closely. The scenario estimates for the year 2050 are sensitive to the assumptions used concerning domestic consumption of wood products. Only the higher decay percent in the non-CCE sector gives a clear decreasing trend for carbon reservoirs in wood products-in-use in 2050.

The expanding carbon reservoirs in wood products in Finland imply that the wood-product sector may be a carbon sink in Finland in the coming decades. In the three scenarios the annual sink in wood products until 2050 was 0.28 Mt, 0.50 Mt, and 0.82 Mt. To shed light on the economic value of this environmental externality of the sector, we evaluated the present value of the predicted sinks in the three scenarios, based on the present value of the offset emissions. With a 4% annual interest rate, a €15/t price for carbon dioxide and two alternative carbon decay functions, the present value (2005) of the wood-product carbon sinks ranged between €440 million and €1380 million. These results show that Finland could be a beneficiary in an international climate regime that would compensate countries for their carbon sinks of wood products, even if only a portion of the climate benefits could be realistically expected to be under a such compensation system.

An international compensation system recognizing carbon sinks in wood products would have to be based on an accurate inventory system. National wood-product inventories would need to be carried out regularly every few years at the minimum, while annual consumption figures and decay estimates could be used to complement the inventory work. A reliable monitoring system would entail obvious costs which would have to be weighed against the climate benefits brought about by the increased use of wood products under such system. The practice where countries are only compensated for a portion of the climate benefits is necessary to bring the system in line with the 'additionality' principle. This principle, which is predominantly followed in the international climate policy negotiations, demands that governments and countries are compensated only for benefits induced by their own actions. In Finland, the government has, in recent years, been sponsoring various programs promoting the use of wood. Part of the increase in the domestic consumption of sawnwood in Finland during the past few years is most likely due to those programs. An international compensatory system would, of course, provide an external incentive for countries to introduce pro-wood policies.

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Notes

1 This sector consists of permanent structures as buildings, contructions, bridges, poles, civil engineering etc.

2 The statistics for the wood panels start from the year 1961, prior to which year their consumption was minimal. We assume therefore that their stock in 1955 was zero. Related technical assumptions used in this study are listed in Appendix 1.

3 The used decay function is similar to the first order decay in IPCC 2006 guidelines, except for the first year construction loss parameter. Especially in the wood based panel case, where the construction losses are high, this gives better approach to estimate carbon storages.

4 Stationarity either after differencing or after fitting a time trend.

5 The standard time series inference presumes stationarity.

6 The estimation of the model (1) is done indirectly by estimating the intercept α in an equation $\Delta y_t = \alpha + \varepsilon_t$.

7 We applied more data-analysis than theory-oriented approach.

8 Testing of the lag length restrictions in some chosen order. This method can lead to the different specification depending on the order of the testing.

9 All the information criteria for the model selection measure the degree of 'in the sample fit', and punish for the number of estimatable parameters in the specification.

10 For dVAR(p), dVARX(p,q) and VECM(p) models p varied from 1 to 5 and q from 0 to 5.

11 Simple combining methods often perform as well as more sophisticated methods (Stock and Watson 2006).

12 In the cases were 10% change gives less than 3 percent actual change is used 50% or 100 change instead of 10%. Also the sensivity analysis for initial sawn wood stock is made by 20% change.

13 The wood house net export analysis is made with known values for the year 1990 and since year 1996. The growth of net export of wood houses between 1990–1996 was assumed to be linear. The analysis including all wood products net export is made with statistics values after 1996. Sources of Foreign trade of finished wood products were Finnish Forest Research Institute 2006, Luoman konserni 2007, Vallin 2007a, 2007b. The corresponding analysis and the analysis concerning higher decay percent are not carried out for the wood-based panels because of lack of statistical sources.

14 In practice, counrties would not be compensated for the full amount of the possible sinks, but rather for only a share of them, as is the case also in terms of the carbon sinks in forests as stated in the Article 3.4 of the Kyoto protocol.

15 The carbon dioxide price in the European Unions emission markets has change betwee 1 to 30 €/t and the carbon-future price of second period allowances are about 15€/t (EU emission allowances 2007, European Carbon Futures 2007).

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Appendix 1. Technical assumptions on the wood materials.

The carbon content wood is assumed to be 51% percent of its dry-material weight. The dry material weight of sawnwood is assumed to bee 0.400 t/m^3, the evergreen sawnwood consumption covers about 97 percent of sawnwoods consumption. The carbon content of sawnwood is then 0.204 t/m^3. The weight of dry wood material in plywood is assumed to be 0.510 t/m^3, so the carbon content of plywood is 0.255 t/m^3. The particle and fibre boards are assumed to contain 90% of wood and the weight of particle board is assumed to be 0.700 t/m^3. The carbon content of particle board is then 0.321 t/m^3. The consumption statics of fibre boards is measured as tons, then the carbon content of fibre boars is 0.459 t/ton of fibre board (Finnish Forest Industries Federation 2002, Puuarkisto 2007).

Appendix 2. ADF unit root test results for consumption series.

The applied test hypotheses were

$$\begin{cases} H_0\text{: Process is a random walk with a drift.} \\ H_1\text{: Process is stationary around a mean.} \end{cases}$$

A significant ADF *t* test value would thus mean stationarity of the tested series.

Series	Level *t*	Level *p*	Difference *t*	Difference *p*
GDP	0.66	0.9899	–3.72	0.0065
Sawnwood	0.39	0.9806	–7.87	0.0001
Plywood	–2.16	0.2226	–8.20	0.0001
Particle board	–1.99	0.2886	–5.85	0.0002
Fibreboard	–2.51	0.1191	–7.51	0.0001

Appendix 3. Selected lag length specification for the VAR models.

Model type	Sawnwood	Plywood	Particle board	Fibreboard
VAR(p)	1	1	3	1
VARX(p,q)	2.1	1.1	3.2	1.1
VECM(p)	2	1	4	2

Appendix 4. Sensitivity analysis: the effect of 10% changes in the assumptions of sawnwood.

		Decay percent (%)	**Change to decay percent** (%)	C stock in 2004 (Mt C)	**Change to 2004 Stock** (%)	C stock in 2050 **Scenario 1** (Mt C)	**Change to C stock 2050 Scenario 1** (%)	C stock in 2050 **Scenario 2** (Mt C)	**Change to C stock 2050 Scenario 2** (%)	C stock in 2050 **Scenario 3** (Mt C)	**Change to C stock 2050 Scenario 3** (%)
Results of the study (Sawn wood)		1.75		23.51		59.67		44.79		35.00	
Sawnwood consumption in	67.5%	1.35	**–23**	26.04	**+11**	66.76	**+12**	51.11	**+14**	40.76	**+16**
CCE sector (75%)	82.5%	2.14	**+22**	21.44	**–9**	53.94	**–10**	39.75	**–11**	30.48	**–13**
Initial carbon stock in CCE sector	4 mill. t[a]	1.61	**–8**	23.62	**0**	61.65	**+3**	46.50	**+4**	36.52	**+4**
at 1955 (5 mill. t)	6.2 mill. t[a]	1.88	**+7**	23.40	**0**	57.93	**–3**	43.28	**–3**	33.67	**–4**
Carbon content of sawnwood	0.184 t/m^3	1.28	**–27**	23.50	**0**	61.25	**+3**	47.02	**+5**	37.60	**+7**
(0.204 t C/m^3)	0.224 t/m^3	2.20	**+26**	23.53	**0**	58.59	**–2**	43.09	**–4**	32.97	**–6**
Construction loss (5%)	2.5%[b]	1.85	**+6**	23.52	**0**	59.58	**0**	44.50	**–1**	34.60	**–1**
	10%[b]	1.54	**–12**	23.47	**0**	59.88	**0**	45.40	**+1**	35.86	**+2**

[a] Using higher change (20%) in the initial carbon stock because uncertainty of initial carbon stock is higher than others

[b] Using double (half) value, while the change with 10% increase (decrease) is less than 3 units

Appendix 5. Sensitivity analysis: the effect of import and export of secondary wood products to sawn wood carbon stock.

		Decay percent (%)	**Change to decay percent** (%)	C stock in 2004 (Mt C)	**Change to 2004 Stock** (%)	C stock in 2050 **Scenario 1** (Mt C)	**Change to C stock 2050 Scenario 1** (%)	C stock in 2050 **Scenario 2** (Mt C)	**Change to C stock 2050 Scenario 2** (%)	C stock in 2050 **Scenario 3** (Mt C)	**Change to C stock 2050 Scenario 3** (%)
Results of the study	All	1.75		23.51		59.67		44.79		35.00	
	Non CCE sector	1.75		5.88		14.92		11.20		8.75	
The approximated volume of net export of wood products	Net export of wood houses[a)]	1.70	**–3**	23.45	**0**	60.31	**+1**	44.54	**–1**	34.16	**–2**
	Net export of wood products sector[b)]	1.64	**–6**	23.35	**–1**	59.95	**0**	44.07	**–2**	33.61	**–4**
Decay percent doubled in Non CCE sector. Initial carbon stock in Non CCE sector as main results (1,66 mill m^3)	All			21.65	**–8**	54.30	**–9**	40.26	**–10**	31.08	**–11**
	Non CCE sector	3.5		3.98	**–32**	9.54	**–36**	6.67	**–40**	4.83	**–45**
Decay percent doubled in Non CCE sector. Initial carbon stock in Non CCE sector 1 mill m^3	All			21.50	**–9**	54.27	**–9**	40.24	**–10**	31.05	**–11**
	Non CCE sector	3.5		3.87	**–34**	9.52	**–36**	6.65	**–41**	4.80	**–45**

[a)] Approximated from euro valued foreign trade statistics for years 1990, 1996–2004 (Finnish Forest Research Institute 2006, Vallin 2007a, 2007b), for years 2004–2050 trade is assumed to be as in the 2004. Used conversion factor for statistics euro values to sawn wood volumes is 1 m^3/ 333 € (Luoman konserni 2007), and construction losses is assumed to be as in domestic use of sawn wood.

[b)] The wood products sector consist on wood houses, door, windows, parquets, furniture, etc. Approximated from euro valued foreign trade statistics for years 1996–2004 (Finnish Forest Research Institute 2006, Vallin 2007a, 2007b), for years 2004–2050 trade is assumed to be as in the 2004. Used conversion factor for statistics euro values to sawn wood volumes is 1 m^3/ 500 €), and construction losses is assumed to be as in domestic use of sawn wood.

Appendix 6. The logistic decay function in present value calculations.

The logistic decay function for wooden material is presented in Eq. 3.

$$remain_{c,t} = e_c * (1 - l) \text{ ; when } t = c$$

$$remain_{c,t} = remain_{c,c} - decay_{c,t} \text{ ; when } t = c + 1$$

where

$$decay_{c,t} = d * remain_{c,c} \tag{3}$$

$$remain_{c,t} = remain_{c,c} - decay_{c,t} \text{ ; when } t > c + 1$$

where

$$decay_{c,t} = (1 - \gamma^{\beta})\, decay_{c,t-1} + \gamma^{\beta} * remain_{c,t-1}$$

In Eq. 3 t is the time and $remain_{c,t}$ is the amount of remain wooden material at year t consumed at year c. e_c is the estimated consumption volume of material at year c. The $decay_{c,t}$ matrix collects the decayed amount of material at year t, which is consumed at year c. The decay in the consumption year is assumed to be zero, because the construction loss parameter l, represented in the chapter 3, determines and includes the first years' decay. The decay at the first year after consumption ($t = c + 1$) is assumed to be the same as the annual decay in the geometric decay functions for materials d. After the second year of consumption the logistic decay is determined as $decay_{c,t} = (1 - \gamma^{\beta})\, decay_{c,t-1} + \gamma^{\beta} * remain_{c,t-1}$, where parameters γ and β define the shape of the function.

For sawnwood the γ parameter is assumed to be 0.0002. Using $\beta = 1.2021$, decay for sawnwood is enforced so that the decay will be 75% in 79 years, as in the geometric decay function. By using parameter values $\gamma = 0.0005$ and $\beta = 1.2668$ the decay of wood-based panels is enforced so that there will be 75% decay in 47 years, as in the geometric decay function of wood-based panels. Construction losses are similar in the cases of both decay functions.

Appendix 7. Sensitivity analysis: the effect of change of interest rate to the present values of carbon reservoirs.

	Interest rate r=4%		Interest rate r=2% (–50%)				Interest rate r=6% (+50%)			
	Decay function		Decay function				Decay function			
	Geometric (mill. €)	Logistic (mill. €)	Geometric (mill. €)	**Change** (%)	Logistic (mill. €)	**Change** (%)	Geometric (mill. €)	**Change** (%)	Logistic (mill. €)	**Change** (%)
Scenario 1: sawnwood products	861	1292	1260	**+46**	1871	**+45**	629	**–27**	949	**–27**
Scenario 2: sawnwood products	593	983	806	**+36**	1341	**+36**	460	**–22**	758	**–23**
Scenario 3: sawnwood products	402	761	496	**+23**	974	**+28**	336	**–16**	615	**–19**
Wood-based panel products	41	86	56	**+37**	108	**+26**	32	**–21**	71	**–17**
All wood products										
Scenario 1	902	1378	1317	**+46**	1979	**+44**	660	**–27**	1020	**–26**
Scenario 2	634	1069	863	**+36**	1449	**+36**	492	**–22**	829	**–22**
Scenario 3	443	847	552	**+25**	1082	**+28**	367	**–17**	686	**–19**

Appendix 8. List of symbols.

α	The intercept (the drift term)
β	Parameters that control the logistic decay function
γ	Parameters that control the logistic decay function
ε_t	White noise process
c	Consumption time (year)
d	The annual decay of material
$decay_{c,t}$	Decayed amount of material at year *t*, which is consumed at year *c*
e_t	Estimated consumption of material at time *t*
l	Parameter that gives losses in the construction process, used as first year decay
$remain_{c,t}$	The amount of remaining material at year *t*, consumed at year *c*
s	The number of the models in forecasts
t	Time (year)
y_t	Value of a stochastic process at time *t*
y_t^{MF}	Median forecast combination for time period *t*