SILVA FENNICA

Vol. 28(2), 1994

SILVA FENNICA
a quarterly journal of forest science

Publishers The Finnish Society of Forest Science
The Finnish Forest Research Institute

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Vol. 28(2) · 1994

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Role of Wood-Based Products in Absorbing Atmospheric Carbon

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Karjalainen, T., Kellomäki, S. & Pussinen, A. 1994. Role of wood-based products in absorbing atmospheric carbon. Silva Fennica 28(2): 67–80.

The amount of carbon (C) stored in wood products manufactured in Finland was calculated with the help of a model using wood harvesting statistics, product flows and lifespans in order to study how much C could be set aside from the atmospheric C cycle outside the forest ecosystem. The calculations showed that on the average 9.9 Tg C/a was in harvested timber in 1986–1991 in Finland. C emissions of timber harvest and transport were 0.1 Tg C/a. In production processes about one third of the C bound in timber was released into the atmosphere, but two thirds was still bound in products. After 50 and 100 years, more than 40 % and 33 % of the C initially in products was either in products still in use or disposed to landfills. The wood product C storage was most sensitive to landfill decay rate and to the burning of abandoned products for energy, but not to the same extent to the length of the lifespan of products.

Keywords carbon balance, timber, wood products, lifespan.
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Accepted August 26, 1994

1 Introduction

A third of the terrestrial carbon (C) in the world is bound in forests and more than 80 % of the global aboveground C is stored in forests (Sedjo 1992), which are thus among the main sinks of atmospheric C. The preservation of the current forests and increasing the size of forested areas are effective way to mitigate the increase in the build up of atmospheric C. At the same time, forests provide raw material for industrial purposes, thus recycling C back to the atmosphere through decay of litter and soil organic matter in humus layer, production processes and decay of products. The amount of C stored in the forest ecosystem is reduced, but partly stored in wood-based products in use or abandoned to landfills, while at the same time the forests are regrowing.

In fact, sustainable use of forests is needed to maintain the sequestration capacity of the forest ecosystem; i.e. the use of stemwood in forest industry makes it possible to remove C into storage outside the forest ecosystem, thus maintaining the sequestration capacity of the forest eco-

system. Based on this rationale, Kyrklund (1990) claims that increasing the production of wood-based products on a sustainable basis in regard the productivity of the forest ecosystem could be the most efficient way to use the forest ecosystem to sequester atmospheric C (see also Dewar and Cannell 1992, Sampson 1992, Marland and Marland 1992, Burschel et al. 1993).

During the last five years several C balance studies have been carried out varying in detail of spatial and temporal scale. These studies are based on field measurements or forest inventory statistics or models or combinations of these all. Most of the studies deal with forest, but some of them include both forest and wood products. Row and Phelps (1990) have developed a model to simulate the flows of C in wood from harvest to final disposition. Dewar and Cannell (1992) assessed with a C storage model C stocks and fluxes in trees, soil and products of different forest plantations in the UK varying in yield class. Kurz et al. (1992) have quantified C storages and fluxes in forest and wood products for one year in Canada, also Burschel et al. (1993) have presented C stocks in forests and wood products in Germany based on estimates of forest inventories and statistics of wood products in use. Seppälä and Siekkinen (1993) have presented C accounting system for use of wood in Finland based on timber statistics.

This study aims to assess and describe the development of C flows in wood-based products in use and abandoned in landfills based on one year timber harvest in Finland to demonstrate the contribution of the wood products in sequestrating atmospheric C. This is done with the help of a model using wood harvesting statistics, timber conversion to products, product lifespan and decay rates in landfills. C flows and storages in wood products were followed 200 years starting with 0 Tg C (1 Tg = 1 Teragram = 10^{12} g) wood product C storage.

2 Computation Methods

2.1 Carbon in Harvested Timber

Conversion of timber into wood products at the first year was based on the average harvest from the years 1986–1991 (Yearbook... 1990–91). Only stemwood exceeding minimum dimensions is harvested in Finland for industrial purposes. The stemwood volume was converted into dry weight and C as in Karjalainen and Kellomäki (1991, 1993); i.e. $MASS = DWD_i \cdot V$, where MASS [kg] is the dry mass of stemwood, V [m^3] is the volume of stemwood and DWD_i is the density of wood [kg/m^3] of the tree species i, and $CMASS_i = CC_i \cdot MASS_i$, where $CMASS_i$ is the C mass [kg] of tree species i, and CC_i is the fraction of C for tree species i (Table 1).

Table 1. Dry weight densities and carbon fractions used in calculations.

Tree species	Basic density DWD, kg/m^3	Carbon fraction CC, dimensionless
Scots pine	390	0.519
Norway spruce	385	0.519
Birch species	490	0.505

Table 2. Annual performances for forest machines and transportation, and carbon emissions per performance.

Machine	Annual performance	Fuel consumption	C emission/performance
Single grip harvester	35000m^3, 2480 h	12 l/h, 0.711 kg/m^3	618 g C/m^3
Forwarder	35000 m^3, 2357 h	8.5 l/h, 0.480 kg/m^3	417 g C/m^3
Truck	31000 m^3, 49 m^3/load, 133 km/load	56 l/100 km, 0.468 kg/km	406 g C/km

C emissions of timber harvest caused by forest machines (single grip harvesters and forwarders) and truck transportation of timber from forest to mills have been assessed using C emission factors for heavy duty diesel vehicles (IPCC 1994) and average annual performances (Yearbook... 1990–91, Oijala et al. 1994) (Table 2) as

$$ME = p \cdot r \quad (1)$$

where ME is machine emission [g C/a], p is annual performance [m^3 or km], and r C emission/performance [g C/m^3 or g C/km].

2.2 Carbon in Wood Products

Calculation of C in wood products is based on a model, which processes harvested timber into products, follows them until they are removed from use and the C bound in them is released back into the atmosphere (Fig. 1). The output of the calculations indicates annually the total amount of C in products in use and in landfills considering the recycling of products and the emission of C back into the atmosphere.

In bookkeeping annual flux of C for the produced products (PP) is calculated as

$$PP_t = TH_{t0} + RC_t - PR_t \quad (2)$$

where TH_{t0} is the C in harvested timber at the beginning, RC is C in recycled products, PR is the C released when burning by-products to generate energy and recycled material converted into recycled products, and t is time (year).

Because all the time some of the products are removed from use, C flux for the products in use (PU) is

$$PU_t = PP_t - RC_t - EP_t - WD_t \quad (3)$$

where EP is the C released when burning discarded products to generate energy, WD is the C

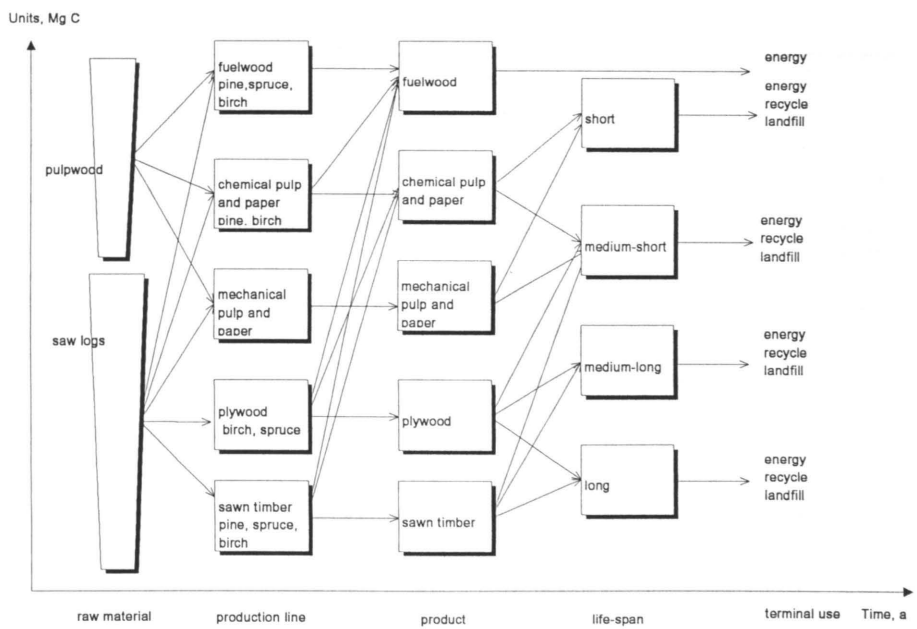

Fig. 1. Outlines of the use of timber in this study.

Table 3. Percentages of different timber assortments used in different production lines.

Production line	Scots pine, %			Norway spruce, %			Birch species, %		
	Logs	Pulp-wood	Residue	Logs	Pulp-wood	Residue	Logs	Pulp-wood	Residue
Sawn timber	100	-	-	92	-	-	11	-	-
Plywood	-	-	-	8	-	-	89	-	-
Mechanical pulp & paper	-	-	-	-	100	-	-	-	-
Chemical pulp & paper	-	100	-	-	-	-	-	100	-
Fuelwood	-	-	100	-	-	100	-	-	100

Table 4. Use of logs and pulpwood (%) in production processes to produce sawn timber, plywood, pulp, and energy.

Use of timber	Logs, %		Pulpwood, %		
	Sawn timber	Plywood	Mechanical spruce pulp	Chemical pine pulp	Chemical birch pulp
Product	43.5	38.4	92.8	45.8	48.6
Processable residue, for pulp	43.5	33.9	-	-	-
Non-processable residue, for process energy	13.0	27.7	7.2	54.2	51.4

in products disposed into landfills.

C flux for the products in landfills (WL) is calculated as

$$WL_t = WD_t - WR_t \quad (4)$$

where WR is the C released into atmosphere from landfills as a constant decay of the C storage in landfills (WL).

Size of the total wood product C storage (WP) has been calculated by adding annual fluxes of the two storages (PU and WL) together

$$\sum_{t=0}^{n} WP_t = \sum_{t=0}^{n} PU_t + \sum_{t=0}^{n} WL_t \quad (5)$$

where n is the time horizon (years).

Timber was divided into three categories (timber assortments) by tree species (Table 3): saw logs, pulpwood and residue wood. Timber can be used in five production lines; i.e. for producing sawn timber, plywood, mechanical pulp and paper, chemical pulp and paper and fuelwood. Saw logs can be used in each production line, but pulp wood only for pulp and paper, as well as for fuelwood, and residue wood only for fuelwood.

The conversion of timber into different products (fuelwood, chemical pulp and paper, mechanical pulp and paper, plywood and saw timber) is based on the amount of timber needed to produce a particular product. The values of the conversion efficiencies are those typical of the current wood-processing industry (Niiranen 1983, Yearbook... 1990–91) (Table 4).

The products were divided into four lifespan categories: short, medium-short, medium-long and long lifespan categories. Short lifespan products include fuelwood, newsprint, some of packing paper, paperboard, and printing and writing paper. Medium-short lifespan products include the rest of the packing paper, paperboard, and

Table 5. Product lifespan parameters and assumed distribution of different products into lifespan categories.

Product lifespan categories	Parameters for Equation 6				Sawn timber	Plywood	Mechanical pulp and paper	Chemical pulp and paper	Fuelwood
	a	b	c	d					
Short	120	5	0.5	120	-	-	34 %	14 %	100 %
Medium-short	120	5	0.15	120	-	-	66 %	86 %	-
Medium-long	120	5	0.065	120	50 %	50 %	-	-	-
Long	120	5	0.03	120	50 %	50 %	-	-	-

printing and writing paper. Medium-long lifespan products include part of sawn timber and plywood, while the rest represent long lifespan products. The lifespans of the products were calculated in the same manner as in Row and Phelbs (1990); i.e.

$$pu = d - \frac{a}{1 + b \cdot \exp(-c \cdot t)} \quad (6)$$

where pu is the fraction of products in use, a, b, d [dimensionless] and c [year^{-1}] are parameters and t is time [year] (Table 5). When a product reaches the end of its lifespan, it can be recycled, used as energy or disposed in landfills. If timber or abandoned products are burnt to generate energy, C is released immediately, while release of C from landfills is slow due to anaerobic conditions of decay. The lifespan of recycled products was shorter or equal to that of the original one; i.e. long lifespan products were recycled into medium-long and short lifespan products were left untouched.

3 Computational Conditions

3.1 Basic Calculations

The calculations are extended over the lifespan of products, thus indicating the capacity of a given cohort of products to retain C from the atmospheric cycle. The calculations concern C in a cohort of wood products manufactured in a given year from the timber harvested in the same year, and the fate of C in different phases of the lifespan of products (Fig. 2); i.e.

- The main part of the C in timber is bound into products while the rest of the C is emitted when by-products (saw dust, bark etc.) are burnt to generate energy,
- Products are in use or they are abandoned,
- Abandoned products can be recycled into raw material again or they can be burnt to generate energy whenever they are removed from use; i.e. the original C in the form of recycled products was used for further production until all the C was emitted into the atmosphere or set aside in landfills or burnt immediately to generate energy with subsequent emissions of C into the atmosphere.

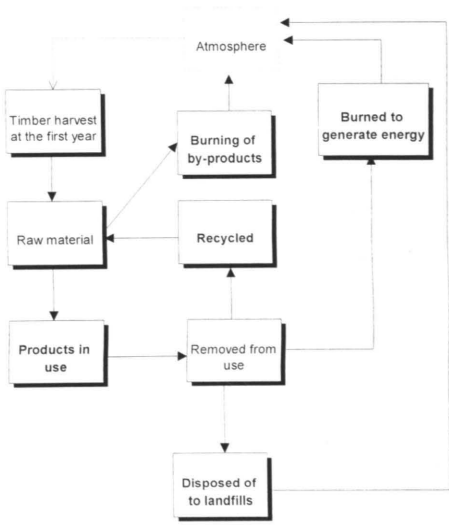

Fig. 2. The transfer of carbon in timber through products into atmosphere.

In the Basic Option, the half lives for different products were 65 years for long lifespan, 30 years for medium-long lifespan, 13 years for medium-short lifespan, and 4 years for short-lifespan products, which were similar or little longer than in Row and Phelbs (1990). Whenever products were removed from use, one third of the products were recycled, one third used to generate energy and one third disposed in landfills. The decay rate of products in landfills was assumed to be 0.5 %/a.

The simulation starts with allocating the C in harvested timber into products and C emitted into the atmosphere in the course of production. Thereafter, C flows into products in the form of recycled products. Again, part of the C is emitted into the atmosphere. At the same time, products are removed into landfills, or burned to energy in which case C is emitted into the atmosphere. This procedure was repeated over a period of 200 years.

3.2 Sensitivity Analysis

First, the amount of C in the cohort of wood products was studied in regard to the distribution of wood-based products into the different lifespan categories by increasing (+10 %, Longer Option) or decreasing (–10 %, Shorter Option) the value of parameter c in the product lifespan equation (equation 6), resulting in 10 % shorter or longer lifespans.

Second, three different terminal use options were used to find out the effect of the end use on the amount of C in wood products. In the Recycle Option, 50 % of the products were recycled when removed from use, 25 % were used to generate energy and 25 % were disposed in landfills. In the Energy Option, 50 % of the products were used to generate energy when removed from use, 25 % were recycled, and 25 % were disposed in landfills. In the Landfill Option, 50 % of the products were disposed in landfills when removed from use, 25 % were recycled, and 25 % were burnt to generate energy.

Third, two different decay rate options were used in the case of release of C from landfills in order to study how the decay rate of wood-based products in landfills affect the respective amount of C; i.e. the decay was enhanced to 1 %/a and to 10 %/a from the original 0.5 %/a.

3.3 Material for Calculations

The timber used to manufacture a cohort of wood products represent the annual average harvest from the period 1986–1991 in Finland on 23.3 million ha area of forest and scrub land (Yearbook... 1990–91). During this period, the average stemwood drain was 11.2 Tg C/a (53.2 million m^3/a) including 1.3 Tg C/a (6.1 million m^3/a) felling residue and natural mortality. The average growth of stemwood in 1986–1990 was 16.9 Tg C/a (80.0 million m^3/a) with a consequent average balance +5.7 Tg C/a (25.1 million m^3/a). The size of the stemwood C storage in 1990 was 394 Tg C equivalent to 1880 million m^3, of which 43.3 % represented Scots pine, 35.3 % Norway spruce and 21.4 % deciduous species (mainly Pendula and Pubescent birch).

The total amount of C in the timber was 9890 Gg C (1 Gigagram, Gg = 10^9 g), representing 790 Gg C in fuelwood, 4120 Gg C in saw logs and 4980 Gg C in pulpwood. Excluding fuelwood, the amount of C in timber used for production was 9100 Gg, of which 1790 Gg consisted of Scots pine logs, 1790 Gg of Scots pine pulpwood, 1960 Gg of Norway spruce logs, 1900 Gg of Norway spruce pulpwood, 370 Gg of non-coniferous logs and 1290 Gg of non-coniferous pulpwood.

C emissions caused by average annual 47.1 million m^3 timber harvest and 127.8 million km transportation of timber from forest to mills have been estimated to total 100.6 Gg C/a (single grip harvesters 29.1 Gg C/a, forwarders 19.6 Gg C/a, trucks 51.9 Gg C/a). Emission of forest machines excluded their transportation (minor importance), but truck emissions included loading (important).

4 Results

4.1 Carbon in Wood Products under Basic Option

The timber used to manufacture the initial cohort of wood products ($P_B(1)$) contained 9890 Gg C (Table 6, Fig. 3). In the production process, about one thirds, 3307 Gg, of C was emitted into the atmosphere when by-products were burnt to generate energy. Consequently, about two thirds, 6583 Gg, of C was bound into products in different product groups and remaining in them as

Product group	Original	Left after 10 years	20 years	30 years
	Gg C	Gg C	Gg C	Gg C
Fuelwood	793	50	0.4	0
Short lifespan	914	369	237	112
Medium-short lifespan	3093	2095	833	225
Medium-long lifespan	891	834	743	633
Long lifespan	891	847	790	724

The amount of C in short lifespan products decreased slower than determined by the lifespan, since substantial amount of medium-short lifespan products were recycled among short lifespan products. Most of the C in use was in medium-long and long lifespan products once 50 years had elapsed from time of production of the original cohort of products (Fig. 4).

During the simulation period (200 years), about 2680 Gg C was recycled; i.e. nearly one third of the C in the timber used by the original cohort of products with the consequence that the amount of C in the produced products during the simulation totalled 8960 Gg C (Table 6). The emissions of production process were about 3610 Gg C when by-products (saw dust, bark etc.) were burnt to generate energy. In all, about 8910 Gg C was set aside in removing products from use with the consequence that only 50 Gg C was in use at the end of the simulation. About 3550 Gg C was emitted into atmosphere when products were burnt to generate energy (including both removed products and fuelwood). Disposition in landfills was 2680 Gg C. As the decay of woody material in anaerobic conditions in landfills was slow,

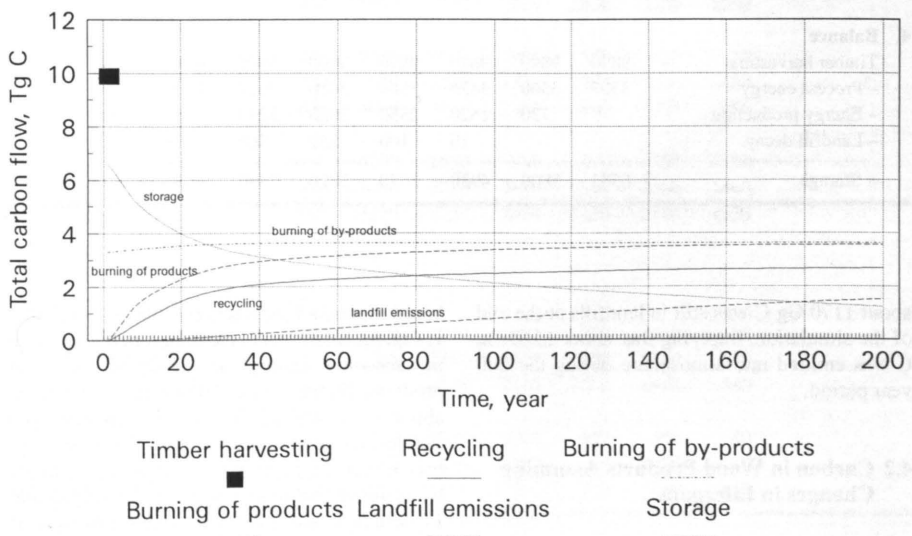

Fig. 3. Carbon flows in wood products.

Table 6. Development of carbon flows in the wood product reservoir in accordance with basic assumptions; cumulative values for different years.

Component / Year	1	5	10	25	50	75	100	200
				Gg C				
1. Production process								
Timber harvesting	9890	9890	9890	9890	9890	9890	9890	9890
+ Recycling		310	750	1710	2200	2380	2500	2680
= Raw material	9890	10200	10640	11600	12090	12270	12390	12570
– Process energy	3307	3360	3420	3560	3610	3610	3610	3610
= Final products	6583	6850	7220	8030	8480	8660	8780	8960
2. Products in use								
Produced products	6583	6850	7220	8030	8480	8660	8780	8960
– Removed from use		1360	3020	5960	7460	8000	8370	8910
= Products in use	6583	5490	4200	2070	1020	660	410	50
3. Terminal use of products								
Recycling		310	750	1710	2200	2380	2500	2680
Energy production		730	1520	2550	3060	3240	3370	3550
Waste to landfills		310	750	1710	2200	2380	2500	2680
– decay			10	100	330	560	780	1510
= Products in landfills		310	740	1610	1870	1820	1720	1170
4. Balance								
Timber harvesting	9890	9890	9890	9890	9890	9890	9890	9890
– Process energy	3307	3360	3420	3560	3610	3610	3610	3610
– Energy production		730	1520	2550	3060	3240	3370	3550
– Landfill decay			10	100	330	560	780	1510
= Storage	6583	5800	4930	3670	2890	2480	2130	1220

about 1170 Gg C was still in landfills at the end of the simulation, implying that about 1510 Gg C was emitted into atmosphere during the 200 year period.

4.2 Carbon in Wood Products Assuming Changes in Lifespans

An increase or decrease of 10 % in the lifespan of products increased or decreased the wood-based products C balance less than 4 %/a (Table 7, Fig. 5). However, in the long run, this resulted in substantial changes in the amount of C in products. During 25 and 100 years, for example, about 11 % and 22 % more C was bound in usable products as compared to the Basic Option, if increased lifespan was assumed. Similarly, during the same time periods about 10 % and 17 % less C was bound in usable products, if decreased lifespan was assumed.

Table 7. The amount of carbon in usable products, and products in landfills as a function of lifespan, terminal use and landfill decay rate.

Option / Year	5	10	25	50	75	100	200
				Gg C			
Basic Option							
Products in use	5490	4200	2070	1020	660	410	50
Products in landfills	310	740	1610	1870	1820	1720	1170
Storage	5800	4930	3670	2890	2480	2130	1220
Changes in lifespans							
1. Shorter Option							
Products in use	5370	4020	1870	930	570	340	30
Products in landfills	350	800	1690	1900	1840	1730	1160
Storage	5710	4830	3560	2830	2420	2070	1190
2. Longer Option							
Products in use	5620	4380	2300	1130	750	500	80
Products in landfills	270	670	1500	1840	1790	1690	1180
Storage	5890	5050	3800	2970	2540	2200	1260
Changes in terminal use							
1. Recycling Option							
Products in use	5620	4430	2320	1200	850	600	120
Products in landfills	240	600	1410	1720	1680	1610	1150
Storage	5860	5030	3740	2920	2530	2220	1260
2. Energy Option							
Products in use	5440	4100	1970	950	590	350	30
Products in landfills	230	540	1130	1310	1270	1190	800
Storage	5670	4640	3110	2260	1860	1550	830
3. Landfill Option							
Products in use	5440	4100	1970	950	590	350	30
Products in landfills	470	1080	2270	2610	2540	2380	1600
Storage	5900	5180	4250	3570	3130	2740	1630
Changes in decay rate							
1. 1 %/a Decay Option							
Products in use	5490	4200	2070	1020	660	410	50
Products in landfills	310	720	1510	1600	1400	1200	540
Storage	5800	4920	3570	2620	2060	1610	580
2. 10 %/a Decay Option							
Products in use	5490	4200	2070	1020	660	410	40
Products in landfills	270	520	570	180	80	50	10
Storage	5770	4720	2640	1200	730	460	50

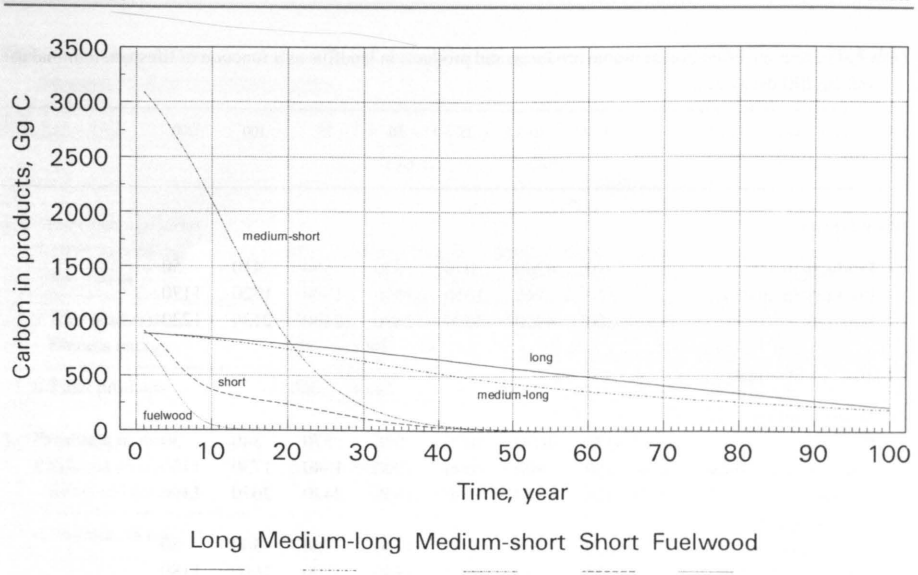

Fig. 4. Carbon in products in use divided into different lifespan categories.

4.3 Carbon in Wood Products Assuming Changes in the Terminal Use

The preference of energy production or landfills in regard to terminal use had a substantial effect on the amount of C in wood-based products as compared to the recycling of terminal use products (Table 7, Fig. 5); i.e. after a simulation period of 25 years, the C balance for the Recycling Option was 1.9 % larger than for the Basic Option, but for the Energy Option it was 15.3 % smaller, and for the Landfill Option 15.8 % larger. Similarly, after a simulation period of 100 years, the total balance for the Recycling Option was 4.2 % larger, for the Energy Option 27.2 % smaller and for the Landfill Option 28.6 % larger than for the Basic Option. At the end of the simulation, the total balance for Landfill Option was 33.6 % larger and for the Energy Option 32.0 % smaller than for the Basic Option.

4.4 Carbon in Wood Products Assuming Changes in Decay Rate

If a decay rate of 0.5 %/a was assumed (Basic Option), the amount of C in landfills culminated in year 58 with a value of 1870 Gg C (Table 7, Fig. 5). If a decay rate 1 %/a was assumed, the amount of C in landfills culminated in year 39 with a value of 1650 Gg C. A further increase in the decay rate to 10 %/a resulted in that the amount C in landfills culminated at the value of 640 Gg C after 18 years from the onset of simulation. In this case, the amount of C in landfills reduced to a value of 50 Gg C in 90 years, while under the Basic Option there was 1760 Gg C still left. If a decay rate 1 %/a was assumed, there was 1270 Gg C in landfills after 90 years simulation. An increase in the decay rate to values 1 %/a and 10 %/a decreased the total amount of C in products in use and in products set aside in landfills by 52 % and 96 %, respectively.

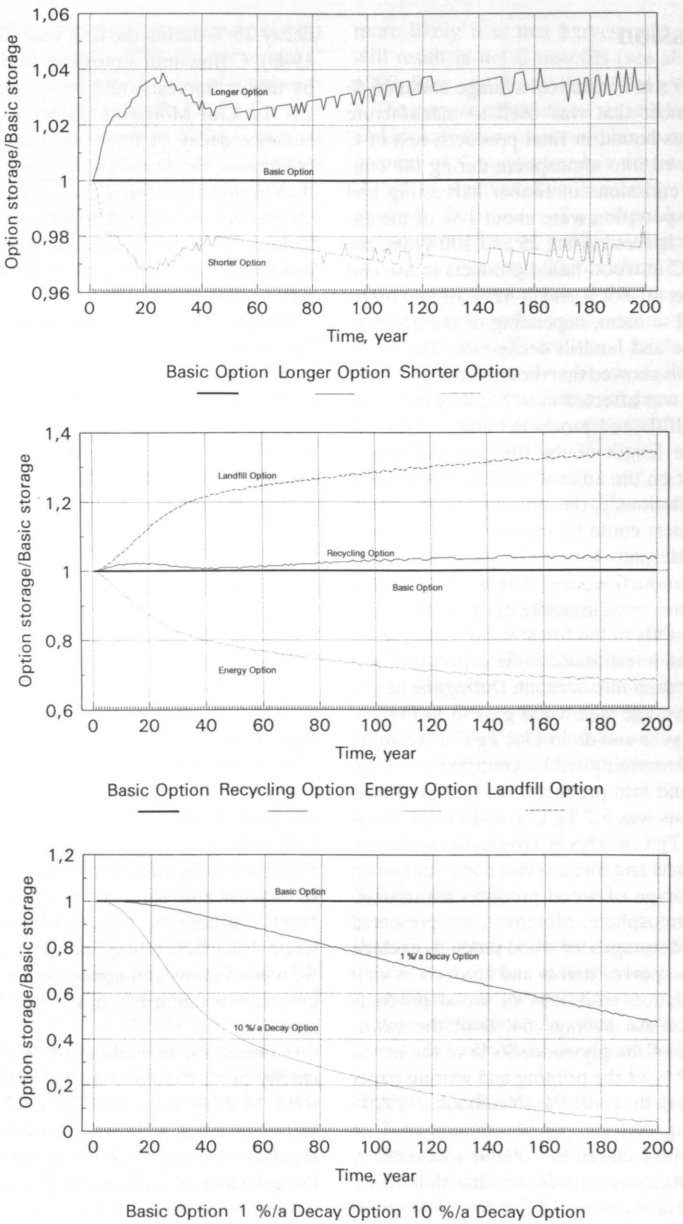

Fig. 5. The wood product carbon balance. Upper: ± 10 % change in product lifespans. Middle: Changes in terminal use, changed form one third to one half. Lower: Change in landfill decay rate.

5 Discussion

In late 1980's in Finland an average about 66 % of C in timber that was used to manufacture products was bound in final products, rest of C being released into atmosphere during the conversion. C emissions of timber harvesting and timber transportation were about 1 % of the annual timber harvest. After 25 and 100 years, the amount of C in wood-based products in use and landfills was 40–65 % and 7–42 % of that originally bound to them, depending of the lifespan, terminal use and landfill decay rate. The sensitivity analysis showed that the amount of C bound in products was affected most of all by the products in landfills and products burnt to generate energy. The length of the lifespan had only a small effect on the amount of C in wood-based products. Obviously, the amount of C in wood-based products could be maximised if products with long lifespans were to be preferred in forest-based production, and if removed products were to be disposed in landfills.

The potentials of the forest sector to sequester C become underestimated if the capacity of forests only is taken into account. During the period 1986–91, average stemwood growth in Finland was 16.9 Tg C/a and drain 11.2 Tg C/a including also natural mortality with a contribution of 6.6 Tg C/a bound into products; i.e. the net C sink for the forests was 5.7 Tg C/a, and for the forest sector 12.2 Tg C/a. This is a overestimate for the wood products and forest sector due to unknown initial C storage of wood products and thus C flow into atmosphere. Moreover, the presented balances and storages for wood products exclude import and export of timber and products as well as transportation emissions of wood products into markets. An average 64 % of the sawnwood, 83 % of the plywood, 86 % of the newsprint and 89 % of the printing and writing paper was exported in 1986–91 (Yearbook... 1990–91), meaning that comparable amount of C in products manufactured in Finland was actually in use and decaying outside the Finnish borders.

As the average amount of C in harvested stemwood was 9.9 Tg C/a, and assuming that the share of stemwood of the total tree biomass is 50–60 %, we get annual felling residue of 7.9–9.9 Tg C/a. If this felling residue is assumed to decay 25 % during the first year (Berg and Staaf 1980), C flow into atmoshere from litter caused by timber harvest could be approximately 2.0–2.5 Tg C/a. Moreover timber harvesting may enhance decay of litter and humus by making conditions for decomposition more favourable than in unmanged forest, although Johnson (1992) claims that no general trend toward lower soil carbon with forest harvesting was apparent, unless harvesting is followed by intense burning or cultivation.

Cooper (1983) has demonstrated that timber harvesting can reduce forest C storage significantly at stand level. Forests will rarely contain more than about one third of the C they could store (averaged over their useful lifetime) if allowed to grow to maximum biomass instead of managed for maximum sustained yield of biomass or to maximize financial return. Old forests are important and big C storages while young and fast growing forest accumulate intensively C. Harmon et al. (1990) assessed conversion of old-growth forest (450-year-old Pseudotsuga-Tsuga natural stand in Oregon, USA) to young plantation (60-year-old Pseudotsuga plantation) to reduce C storage as much as 305 Mg C/ha, even though conversion of timber into products were included.

When considering forest C storages, one should keep in mind that stemwood C storage is one compont of the total storage. Karjalainen and Kellomäki (1991, 1993) have estimated that in Finland C in stemwood accounted only about 15 % of the whole forest C storage of 2802 Tg in 1990. Furthermore tree stand including stemwood, branches, foliage and roots accounted 26 %, while humus and upper soil layer 73 %, and ground vegetation 1 % of the total forest C storage.

C emissions in Finland of fossil fuels from energy production and traffic in the late 1980s were 14.2 Tg C/a (Boström et al. 1990). The sequestration of C in wood-based products and regularly managed forests in accordance with the principle of sustainability seem to provide potentials for reducing emissions of carbon dioxide (CO_2) into the atmosphere. The case of Finland is applicable for countries with a predominance of forests in regard to the total land area and large forest area per capita. For example in New Zealand, MacLaren et al. (1993) estimated that in the late 1980s the net annual C uptake of the 1.24 million hectares of plantation forests was 4.3 Tg C/a (growth 7.8 Tg C/a and removals 2.8 Tg C/a); i.e. 60 % of the C emitted annually (7.2 Tg C in 1988). The role of forests is much smaller in Germany (Burschel et al. 1993), where forests absorb about 5.5 Tg C/a (annual increment of the growing stock 18.1 Tg C/a and timber harvesting 12.5 Tg C/a); i.e. about 2 % of that annually emitted (about 260 Tg C/a). However, the sequestration of C in the forest sector is not a final solution even in countries with large forest resources, since the C will, in the long run, saturate the forest ecosystem and storages outside forest lands. Therefore, the sequestration of C in the forest sector will only serve to provide us with extra time in which to implement proper technology for reducing C emissions. Schroeder and Ladd (1991) conclude that conserving the existing forests is an immidiate and direct contribution to solving the CO_2 problem rather than planting new trees, but in practice this seems to be impossible and in the long run does not give mitigation benefits, rather sustainable use of land could give direct contribution (Detwiler and Hall 1988).

Marland and Marland (1992) suggest that trees are equally effective in reducing the accumulation of CO_2 in the atmosphere if trees remove a unit of C from the atmosphere or if trees provide a sustainable source of energy that substitutes for a unit of C emitted in burning fossil fuels. This implies that the most effective strategy for using forest land to slow down the increase of atmospheric CO_2 depends on the current status of the forests, the expected productivity, the efficiency with which timber harvested can be used to substitute fossil fuels, and the time perspective of the analysis. In the case of forests with large standing biomasses and low productivity, the most effective strategy is to reforest or otherwise manage the land so as to maintain forest growth and C storage. Where high productivity can be expected, the most effective strategy is to manage the forest for timber crops and to use the harvested timber with maximum efficiency either for long-lived products or as substitutes for fossil fuels (Marland and Marland, Burschel et al. 1993). The longer the time perspective, the more likely it is that harvest and reforestation will result in net C benefits (see also Kyrklund 1990, Row and Phelps 1990, Sampson 1992).

The present calculations are still tentative ones and include many uncertainties, even though the amount of C sequestered in forest growth and stored in stemwood is accurately known. For example, the amount of wood products in use or the amount of wood products disposed in landfills is not known. This makes it difficult to compare the total sizes of the forest and wood product C reservoirs. Furthermore, the estimates of lifespan for different wood products could be inaccurate just like the amount of different products being recycled, burnt or disposed in landfills. If products are recycled, most of the C will be kept in use, but released directly in the atmosphere if the products are burnt. Similarly, the decay rate of waste in landfills varies.

Acknowledgements

We thank Mr. Mauri Aantio for his help with plywood product converision figures, Mr. Antti Asikainen for his help with forest machine and transportation C emission assessment, and Mr. Gert-Jan Nabuurs for his comments on the manuscript.

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