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Approaches for Carbon Budget Analyses of the Siberian Forests

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Foreword

Siberia's forest sector is a topic, which has recently gained considerable international interest.

IIASA, the Russian Academy of Sciences, and the Russian Federal Forest Service, in agreement with the Russian Ministry of the Environment and Natural Resources, signed agreements in 1992 and 1994 to carry out a large-scale study on the Siberian forest sector. The overall objective of the study is to focus on policy options that would encourage sustainable development of the sector. The goals are to assess Siberia's forest resources, forest industries, and infrastructure; to examine the forests' economic, social, and biospheric functions; with these functions in mind, to identify possible pathways for their sustainable development; and to translate these pathways into policy options for Russian and international agencies.

The first phase of the study concentrated on the generation of extensive and consistent databases for the total forest sector of Siberia and Russia.

The second phase of the study encompasses assessment studies of the greenhouse gas balances, forest resources and forest utilization, biodiversity and landscapes, non-wood products and functions, environmental status, transportation infrastructure, forest industry and markets, and socioeconomic problems.

This report carried out by Timo Karjalainen, University of Joensuu, Finland (currently European Forest Institute, Joensuu, Finland) and Jari Liski, University of Helsinki, Finland during their stay at IIASA in 1996, is a contribution to the analyses of carbon balances of the Siberian forests.

The report contains two inter-linked sections. The first is on a method to assess the development of tree biomass carbon in Siberia written by Karjalainen and the second deals with the carbon balance of the Siberian forest soils written by Liski. Ari Pussinen, University of Joensuu, Finland, has written the computer code for the ecoregional simulations on the biomass development.

Acknowledgments

Contents

A Method for Assessment of the Development of Tree Biomass Carbon Pool in Siberia

Timo Karjalainen

Abstract

The aim of this study was to develop a method for assessments of carbon budgets for tree biomass at ecoregional level in Siberia. The aim of this study is to develop a method to assess carbon budget for tree biomass at ecoregional level in Siberia.Tree biomass carbon budgets contain estimates on the initial amounts of carbon in the whole tree biomass, as well as its dynamics. The calculation method developed is based on the structure of the Russian Forest database available at IIASA and available models describing tree growth and biomass allocation in Siberia. Calculated litter production is used as input for separate calculations on the soil organic matter carbon budget (Liski, 1997).

Stand level analyses showed that the developed method describes vegetation carbon budget in a plausible manner. The stand level analyses are the platform for aggregated regional assessments. There are, however, several matters that should be taken into account in the regional assessments. These relate to stand structure, description of stand replacing disturbances, and availability of data.

1. Introduction

Carbon balance studies have been done for different spatial scales, from stand level to global level. Examples on global studies are mentioned; Dixon *et al.* (1994), Nilsson and Schopfhauser (1995), and Houghton (1996), on a continental scale, for Europe, Kauppi *et al.* (1992), and for tropical regions Brown and Iverson (1992). Several studies have been done at the country scale, e.g. in Canada Kurz *et al.* (1992), in Britian Dewar and Cannell (1992), in New Zealand Hollinger *et al.* (1993), in Germany Burschel *et al.* (1993), in Sweden Eriksson (1991), in Finland Karjalainen and Kellomäki (1993), and in Russia Isaev *et al.* (1995). Stand level studies have been done by e.g. Cooper (1983), Harmon *et al.* (1990), Nabuurs and Mohren (1993), and Karjalainen (1996a). The assessments can cover history, portray single years, or give predictions on future dynamics also, the details included in the assessment may vary (Nabuurs, 1994). Usually carbon budget assessments contain both the size of the assessed carbon storage, and the carbon flows between the assessed storage and the atmosphere (*Table 1*).

Table 1. Sizes of carbon pools in the boreal forest zone.

Region	Year	Biomass, Tg	Soil, Tg	Products, Tg	Total, Tg	C density, Mg/ha	Net sequestration, Tg/a	Fossil emission, Tg/a	Source
Canada[1]	1990	7100	51700	300	59100	195	-75.0	119	a
Alaska	1992	2358	13637		15996	306			b
Sweden	1990	730			730	26	9.3	18	c
Finland	1990	660	7565	40	8265	355	8.8	15	d
European Russia	1988	7639			7639	46	[2]60.0		e
Russia	1988	50403	349534		399937	500	853.0		f
Russia	late 80s	44000	117000		161000	246	410.0	800	g
Russia		35070			35070	41	213.0		h
Russia		27980	90848		118828	154			i
Russia	1988	42100		2900	45000	51			j
Russia	1993	33900			33900	38			k
Russia			320635		320635	360			l
Boreal	late 80s	88000	471000		559000	407	480.0		m
Boreal	1980	96000	237000		333000	285			n

[1] boreal Canada, soil excluding peat, [2] calculated for the period 1988-1993

a) Kurz and Apps 1996, b) Birdsey *et al.* 1995, c) Sweden's National Report 1995, d) Karjalainen and Kellomäki 1996, Liski and Westman 1997, Ahlholm and Silvola 1990, e) Lakida *et al.* 1996, f) Kolchugina *et al.* 1993, g) Kolchugina and Vinson 1995, h) Isaev *et al.* 1995, i) Alexeyev *et al.* 1995

j) Krankina *et al.* 1996, k) Shvidenko and Nilsson 1996, l) Rozhkov *et al.* 1996, m) Dixon *et al.* 1994, n) Houghton 1996

The traditional approach for carbon budget assessments is conversion of forestry statistics into carbon, but also geo-chemical dynamic models have been developed and used. The first thorough carbon balance model for a complete forest sector in a country was developed by Kurz *et al.* (1992) in order to assess the Canadian forest sector carbon budget. There is no general consensus on the methods for assessments of carbon budgets, although Intergovernmental Panel on Climate Change (IPCC) has tried to standardize national greenhouse gas inventories (IPCC 1993), in which also forest and land-use change carbon budgets are included.

A substantial proportion of the global forest carbon storage is located in the boreal forests, the extent has been estimated to contain 30-50% of the global forest carbon (Dixon *et al.* 1994, Houghton 1996). In the boreal zone, a large proportion of the carbon is sequestered by the soil, some 70-90% of the total carbon (*Table 1*). In addition, a substantial proportion of the soil carbon is located in peat lands, e.g. in Finland approximately 80%. The size of the boreal vegetation carbon pool is 40-96 Pg, and the soil carbon pool is 164-471 Pg.

As a consequence of changing climate, boreal forests are likely to decrease in area, biomass and carbon stock (Neilson *et al.* 1993, Dixon *et al.* 1994, Kurz and Apps 1994, and Wang and Polglaise 1995). The extent of the forest carbon sink in the boreal zone will, however, likely be reduced in the future even without climate change, and the biome could turn to a carbon source due to changes in disturbance regimes and age-class structures (Apps *et al.* 1993). This is likely to happen in areas where the major proportion of the forests are unmanaged and due to the fact that suppressions of large scale disturbances in remote areas are difficult. Recently, forests in Canada and Russia have been reported to have turned to a carbon source (Kurz and Apps 1996, Shvidenko *et al*. 1996a). In Finland, however, forests are predicted to increase the sequestration of carbon in the future if the current management regimes are not changed substantially (Karjalainen *et al.* 1995, Karjalainen and Kellomäki 1996). The reason for this development is that the harvesting affects the carbon balance more than natural disturbances in Finland.

Terrestrial ecosystems exchange carbon with the atmosphere of about 60 Pg annually, which is almost ten times more than the carbon emissions from land-use change (1.6±1.0 Pg C/a) and fossil fuel combustion (5.5±0.5 Pg C/a) (Houghton *et al.* 1995). Therefore, already small changes in the processes of the terrestrial carbon reservoir can substantially influence the global carbon balance. Since the boreal forests have been argued to constitute a substantial carbon sink (Ciais *et al.* 1995, Houghton *et al.* 1995, Schimel 1995), reliable estimates on the magnitude of this sink and the dynamics are urgently needed. Russian forests cover some 65% of the northern forests. Estimates on the size of the carbon storage and carbon sequestration by the Russian forests vary markedly (*Table 1*). Accurate estimates on the Russian forest carbon budget would improve both the boreal and the global carbon budgets (Shvidenko *et al*. 1996a).

2. Aim of the study

Estimates on the size of the Siberian and Russian forest carbon stock and net sequestration vary substantially, but the conclusion is that they are an essential part of the boreal and global forest carbon budgets (see *Table 1*). Accuracy of the Siberian and Russian forest carbon stock sizes have substantial effect on the whole boreal and global estimate, too.

The aim of this study is to develop a method to assess carbon budget for tree biomass at ecoregional level in Siberia. The carbon budget of tree biomass include estimates on the initial amount of carbon of the total tree biomass, as well as the future carbon dynamics. The database of the Russian forests at IIASA contains information on 165 ecoregions, of which 63 are located in Siberia. The calculation method developed is based on the structure of this database and the available models describing tree growth and biomass allocation in Siberia. Litter production calculated by this model will be used as input for calculation of the carbon budget for soil organic matter (Liski 1997).

3. Method

3.1. Input data

IIASA has gathered a database over the forest sector of Russia. An essential part of this database is information on the forest resources. The latest available information is from the 1993 State Forest Account. Although the amount of information is huge, the level of aggregation varies and makes the use of the database complicated, i.e. some of the information may be at species level but some at species group level.

Calculation of initial carbon budget for tree biomass requires that the volume of the standing stemwood stock has to be converted into total tree biomass with allocation equations. This requires information on the site class conditions of the forests, density of the growing stemwood stock, and age class structure, i.e. current structure of the forests. Required information exists on ecoregion level in the database. Ecoregions are defined as combinations of administrative and ecological polygons with similar properties (Shvidenko *et al*. 1996a). In order to assess the development of the forests and hence the carbon budget, forest growth models are needed as well as information on the factors that affect the stemwood stock development, like extent of timber harvesting and natural disturbances.

Most of the basic input data required for the calculations can be found in the State Forest Account (SFA). The information includes forest land area and volume of the growing stock distributed over age classes (5 classes) which are further broken down into forest classes (the forests are grouped according to the levels of management and protection into 54 sub-classes) and species. In addition, information is available on forested area by site index (5 classes), density (6 classes) and age (4 classes), and on species group level (3 classes). Since the basic data are available at different levels of aggregation, at species level and at species group level, calculations should be done at the level with least accurate data, i.e. at species group level. The species proportions can be used, however, for different weighing purposes at the species group level.

The data used from the IIASA databases are presented in Table 2. As basic calculation units are state variable objects (SVOs), which are a collection of state variables and their dynamic behavior. A SVO can be considered as a group of areas which have similar properties, i.e. similar species, stand age, and management regime. Each SVO has to be formed based on the initial data, and they include e.g. area and volume.

Table 2. Input data from IIASA databases. SFA refers to data from the State Forest Account database and ER to data from the Ecoregion database at IIASA.

TABLE	Data column	Description
SFA200	er-id	ecoregion identifier
	protection	forests in different classes of management/protection, 54 classes (protection is equal to Forest-class in SFA100)
	cutting-age	code for age class limits and for cutting age/age at maturity
	species-code	dominant tree and shrub species
	FL-tot	area of forest land, in 100 ha
	FL-yng-1cl	area of forest land of 1st young class
	FL-yng-2cl	area of forest land of 2nd young class
	FL-mdl-tot	area of forest land of middle age class
	FL-matrig	area of forest land of maturing class
	FL-omat-tot	area of forest land of mature and overmature class
	ST-tot	total living stemwood stock, in 10000 m^3
	ST-yng-1cl	living stemwood stock of 1st young class
	ST-yng-2cl	living stemwood stock of 2nd young class
	ST-mdl-tot	living stemwood stock of middle age class
	ST-matrig	living stemwood stock of maturing class
	ST-omat-tot	living stemwood stock of mature and overmature class
SFA307	er-id	ecoregion identifier
	age-density	stand density class (6) and age class (4)
	SW-hc12	area of coniferous species in Ia and Ib-II site class, in 100 ha
	SW-hc3	area of coniferous species in III site class
	SW-hc4	area of coniferous species in IV site class
	SW-hc5	area of coniferous species in V site class
	SW-hc5ab	area of coniferous species in Va and Vb site class
	SW-tot	area of coniferous species total
	BL-hc12	area of deciduous hard species in Ia and Ib-II site class
	BL-hc3	area of deciduous hard species in III site class
	BL-hc4	area of deciduous hard species in IV site class
	BL-hc5	area of deciduous hard species in V site class
	BL-hc5ab	area of deciduous hard species in Va and Vb site class
	BL-tot	area of deciduous hard species total
	OHW-hc12	area of deciduous soft species in Ia and Ib-II site class
	OHW-hc3	area of deciduous soft species in III site class
	OHW-hc4	area of deciduous soft species in IV site class
	OHW-hc5	area of deciduous soft species in V site class
	OHW-hc5ab	area of deciduous soft species in Va and Vb site class
	OWH-tot	area of deciduous soft species total
ER3114	er-id	ecoregion identifier
	AA-cw-con	annual allowable commercial cut of coniferous wood, in 100 m^3
	AA-cw-har	annual allowable commercial cut of deciduous hard species
	AA-cw-sof	annual allowable commercial cut of deciduous soft species
ER3115	er-id	ecoregion identifier
	Cutt-type	clear cuttings, gradual and selective harvests, clear sanitary harvests, other
	Fh-cw-coni	actual final commercial harvests of coniferous wood in 1991, in 100 m^3
	Fh-cw-hard	actual final commercial harvests of deciduous hardwood in 1991
	Fh-cw-soft	actual final commercial harvests of deciduous softwood in 1991
ER3122	er-id	ecoregion identifier
	Ff-year	year 1989, 1990, 1991
	Ff-tot	area destroyed by forest fire, in ha
	Ff-crown	area of crown fires

3.2. Formation of state variable objects (SVOs)

The first step of the calculations is to form the proportions for each tree species based on the volume data (SFA200) for I, II, and III forest groups. The forests have been divided into these groups based on the intensity of exploitation and protection. The first group forests are under special protection, second group forests are under restricted industrial use, while the third group forests are mainly exploitable forests.

The second step of the calculation is to divide volumes and areas from SFA200 for stand ages. SFA200 does not contain actual stand ages, but a code (cutting-age) for age class limits. Actual age class limits can be found in Russian forest inventory instructions. Therefore, age class limits are given in a separate table (*Table 3*).

Table 3. Age class limits and cutting age / age of maturity.

		Age classes										
Code	Cutting age/ age of maturity	Young, 1st lower	upper	Young, 2nd lower	upper	Middle-aged lower	upper	Immature lower	upper	Mature lower	upper	Overmature lower
5	281	1	40	41	80	81	240	241	280	281	360	361
9	241	1	40	41	80	81	200	201	240	241	320	321
13	201	1	40	41	80	81	160	161	200	201	280	281
15	181	1	20	21	40	41	160	161	180	181	220	221
17	161	1	20	21	40	41	140	141	160	161	200	201
21	141	1	20	21	40	41	120	121	140	141	180	181
25	121	1	20	21	40	41	100	101	120	121	160	161
29	101	1	20	21	40	41	80	81	100	101	140	141
33	81	1	20	21	40	41	60	61	80	81	120	121
35	71	1	10	11	20	21	60	61	70	71	90	91
37	61	1	10	11	20	21	50	51	60	61	80	81
39	51	1	10	11	20	21	40	41	50	51	70	71
43	41	1	10	11	20	21	30	31	40	41	60	61
44	36	1	5	6	10	11	30	31	35	36	45	46
46	31	1	5	6	10	11	25	26	30	31	40	41
47	26	1	5	6	10	11	20	21	25	26	35	36
48	21	1	5	6	10	11	15	16	20	21	30	31
54	16	1	2	3	4	5	12	13	14	15	18	19
62	11	1	2	3	4	5	8	9	10	11	14	15
68	9	1	1	2	2	3	7	8	8	9		
71	8	1	1	2	2	3	6	7	7	8		
73	7	1	1	2	2	3	5	6	6	7		
75	6	1	1	2	2	3	4	5	5	6		
77	5	1	1	2	2	3	3	4	4	5		
79	4	1	1	2			2	3	3	4		
81	3	1					1	2	2	3		
83	2	1						1	2			
85	1	1							1			

The distribution of volumes and areas of an actual stand age is unknown, therefore an even distribution is assumed for each stand age, i.e. 100/(upper limit - lower limit) in each age class. Volumes and areas are distributed by species over forest groups I, II, and III. By this calculation, volumes and areas are classified based on protection classes and species for each stand age. This classification is also the basis for SVO definition (the attributes are now species, stand age, area in a forest class, and volume).

The third step is to aggregate volumes and areas at each stand age to species group level by summing them up for coniferous, deciduous hard and deciduous soft groups.

The fourth step is to aggregate protection classes to forest groups (3 groups) and divide forest groups to exploitable and non-exploitable categories based on forest classes in each group. The SVOs are by this defined by forest groups (3*2), species groups (3), and stand age (approximately 400 years) and include volume and area.

The fifth step is to include site indexes and densities in the SVOs. The site index describes the growing conditions (quality scale, 5 classes are defined as Ib&Ia - II, III, IV, V, Va&Vb), from best to worst. The density describes the stocking (standing volume) of the stands (6 classes as proportions of full stocking (1.0) are 0.3-0.4, 0.5, 0.6, 0.7, 0.8, 0.9-1.0). Site indexes and densities are needed for the growth calculations. Site indexes and densities are given at species group level, but not at the forest group level. Since areas given in the State Forest Account and in the SVO do not necessarily match, area proportions have to be calculated based on age and density and assuming that density and site index are distributed in a similar way in all forest groups. Volumes and areas in the different forest groups are multiplied with these proportions. Site index classes are given (N) as:

Site index	Ia and Ib - II	III	IV	V	Va and Vb
N	2	4	5	6	7

By these calculation steps the SVOs have volume and area over forest groups (3*2), by species groups (3), by stand age (approximately 400 years), site indexes (5), and densities (6). Approximately 216000 SVOs have been formed (*Figure 1*) for the test ecoregion of Angara-Lena Southern Taiga used for the calculations.
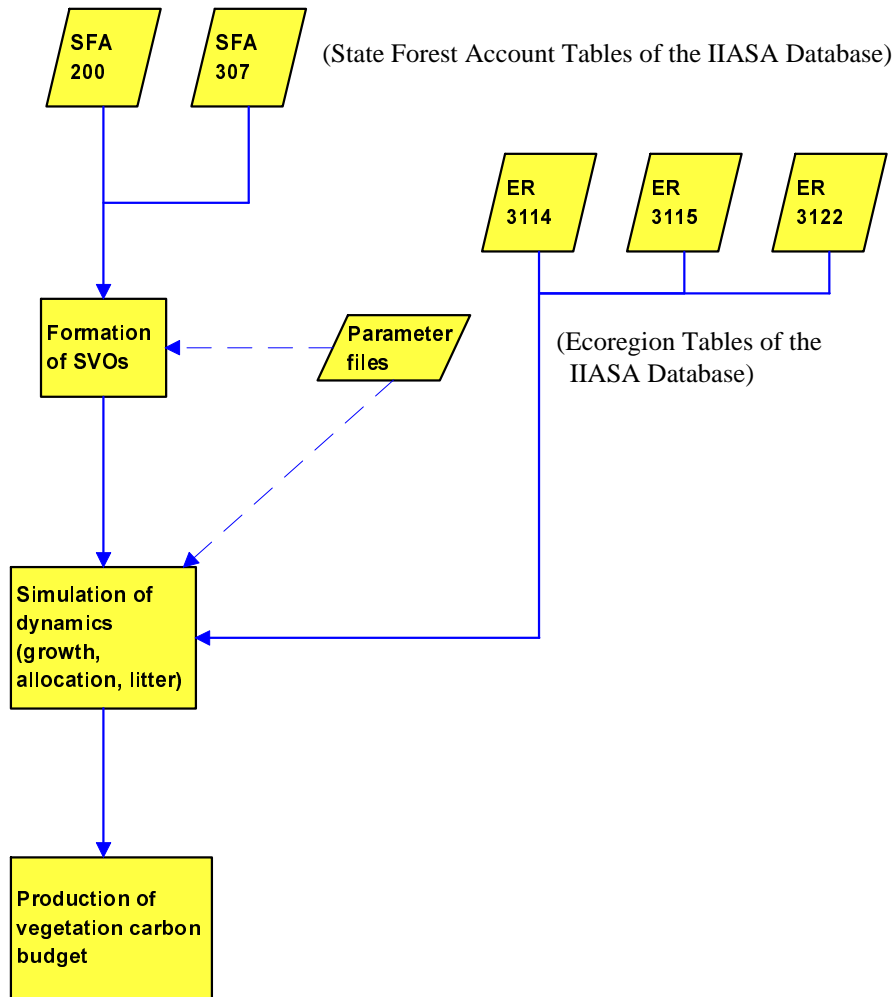
Figure 1. Outline of calculations.

3.3. Calculation of growth

The calculation of annual gross increment (*dTV*), net increment (*dGS*), and natural mortality (*dM*) for SVOs is based on equations produced by Shvidenko *et al.* (1996), and Shvidenko and Venevsky (1996):

$$dTV = b_1 \cdot b_2 \cdot b_3 \cdot (1 - e^{-b_2 \cdot A})^{(b_3 - 1)} \cdot e^{-b_2 \cdot A}$$

$$dGS = c_1 \cdot c_2 \cdot c_3 \cdot (1 - e^{-c_2 \cdot A})^{(c_3 - 1)} \cdot e^{-c_2 \cdot A}$$

where *A* is stand age, and b_1, b_2, b_3, c_1, c_2, and c_3 are coefficients, which are tree species specific and also dependent on the site index (*N*), and density (*d*).

Coefficients are calculated as

$$b_1 = b_{120} \cdot N^2 + b_{110} \cdot N + b_{102} \cdot d^2 + b_{101} \cdot d + b_{122} \cdot d \cdot N + b_{100}$$

$$b_2 = b_{220} \cdot N^2 + b_{210} \cdot N + b_{202} \cdot d^2 + b_{201} \cdot d + b_{222} \cdot d \cdot N + b_{200}$$

$$b_3 = b_{320} \cdot N^2 + b_{310} \cdot N + b_{302} \cdot d^2 + b_{301} \cdot d + b_{322} \cdot d \cdot N + b_{300}$$

$$c_1 = c_{120} \cdot N^2 + c_{110} \cdot N + c_{102} \cdot d^2 + c_{101} \cdot d + c_{122} \cdot d \cdot N + c_{100}$$

$$c_2 = c_{220} \cdot N^2 + c_{210} \cdot N + c_{202} \cdot d^2 + c_{201} \cdot d + c_{222} \cdot d \cdot N + c_{200}$$

$$c_3 = c_{320} \cdot N^2 + c_{310} \cdot N + c_{302} \cdot d^2 + c_{301} \cdot d + c_{322} \cdot d \cdot N + c_{300}$$

Natural mortality (*dM*) is calculated based on gross production (dTV) and net production (dGS) as

$$dM = dTV - dGS$$

Parameters for the calculation of the coefficients are given in a separate file and in the current calculations general estimates for total Siberia have been used (*Table 4*). Since estimates are not available for all individual tree species, the most similar species estimates available have been used. For fir the spruce parameters were used, for cedar and juniper the pine parameters were employed, for deciduous hard species the oak parameters were used, for gray and black alder the birch parameters were used, and for lime, poplar and willow the aspen parameters were employed. Since species are aggregated to species groups, species proportions based on volume calculated earlier as weights are used when calculating the coefficients. The use of these weights bring the current species structure into the growth calculations. If species structure is ignored, growth calculations would be biased, since growth of different tree species vary significantly. In the current calculations these weights are not assumed to change over time.

In *Figures 2* and *3* the dynamics of the growing stemwood stock, gross and net production and natural mortality calculated by the above equations are presented. Shvidenko *et al.* (1996b) conclude that the equations match quite well with the general growth and yield tables of fully stocked evenaged stands in Russia.

Each simulation (initial simulation year is 1990) is carried out on a yearly basis. Development of the growing stemwood stock is calculated as:

$$GS_{year} = GS_{init}$$

$$GS_{year+1} = GS_{year} + dGS_{year+1} - HARV_{year+1} - DIST_{year+1}$$

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and etc. Gross production and natural mortality also have to be calculated, since natural mortality is needed for upcoming litter calculations.

HARV is harvesting and DIST is disturbances other than those included in the natural mortality (due to self thinning, aging, insect and disease outbreaks and ground fire). Both HARV and DIST are stand replacing disturbances, and therefore, harvested and disturbed areas have to be removed to stand age 0, but assuming same tree species, site index and density as initially in the simulations.

Table 4. Parameters for calculation of the coefficients for the growth equations (Shvidenko and Venevsky 1996).

	Species					
parameter	pine	spruce	larch	oak	birch	aspen
b_{100}	207.4674	180.5888	14.89885	637.9028	199.2417	260.4649
b_{101}	1778.316	2606.015	1508.967	1246.599	1115.688	1263.355
b_{102}	-193.159	-489.992	-1.30E-10	41.38131	-259.828	-333.67
b_{110}	-66.9821	-51.8728	-67.6981	-64.2541	-80.4278	-112.257
b_{120}	4.173756	0.47205	8.167804	-1.16365	6.250513	10.80118
b_{122}	-174.997	-229.123	-174.997	-178.811	-98.4463	-103.653
b_{200}	0.042285	0.023864	0.044226	0.025627	0.048304	0.051285
b_{201}	-0.02136	-0.00294	-0.01773	-0.00865	-0.01932	-0.01112
b_{202}	0.003624	0.001729	2.11E-15	0.002126	-0.00372	-0.00685
b_{210}	-0.0043	-0.00038	-0.00304	-0.0029	-0.00209	-0.00049
b_{220}	0.000342	-7.70E-05	0.000024	0.000361	-0.00003	-4.90E-05
b_{222}	0.001129	0.000014	0.001129	0.000793	0.001882	-0.00035
b_{300}	2.768428	2.712135	2.5861	2.987432	2.37	2.617857
b_{301}	-1.29628	-0.29837	-0.36643	-1.69441	-1.33322	-0.54505
b_{302}	0.822985	0.290073	3.86E-13	0.759964	0.407693	0.106591
b_{310}	-0.2872	0.304812	-0.19843	-0.11953	0.116397	-0.02748
b_{320}	0.0389	-0.02972	0.017095	0.035984	-0.00487	-0.00362
b_{322}	0.077631	-0.00799	0.053008	-0.0597	0.113229	-0.00104
c_{100}	13.23984	124.0545	-53.8572	-93.247	-25.3732	-27.8481
c_{101}	878.7605	1372.634	870.1806	849.9144	629.4216	674.9466
c_{102}	93.63118	-54.7459	118.3955	381.1728	81.68202	111.3739
c_{110}	-22.138	-69.644	-16	26.05641	-9.87134	6.617726

c_{120}	3.802649	7.802248	2.762214	0.87217	3.166198	0.375203
c_{122}	-121.08	-166.021	-114	-162.108	-101.672	-98.2327
c_{200}	0.029244	0.024618	0.056032	0.017952	0.026576	0.036346
c_{201}	-0.002	0.000243	-0.02249	0.000832	-0.00304	-0.0025
c_{202}	0.000203	7.87E-05	0.010626	-3.50E-05	0.001589	0.000382
c_{210}	-0.0025	-0.00103	-0.00978	-0.00104	-0.00013	-0.00573
c_{220}	0.000156	-2.80E-06	0.00083	0.000226	5.89E-05	0.000574
c_{222}	0.0002	-7.20E-05	-0.00013	-0.00015	-0.00013	0.000243
c_{300}	2.092845	2.826917	3.541151	1.588481	1.126933	1.708474
c_{301}	-0.07705	0.040252	-0.47666	0.08071	0.167419	0.002149
c_{302}	0.011944	-0.02571	0.046502	0.031384	-0.04063	-0.00107
c_{310}	-0.07196	0.010275	-0.76431	-0.05392	0.178273	-0.12874
c_{320}	0.013303	0.013694	0.085249	0.025634	0.006152	0.01905
c_{322}	0.008194	-0.01732	0.028297	-0.03321	-0.00943	0.013201

The harvest carried out in Siberia is dominated by clearcuts, therefore we assume only clearfelling in the simulations and they should begin in the oldest stand ages in those forest groups where harvesting is allowed. The harvesting volumes of the different cutting types identified in the database are added together and regarded as clearcuts.
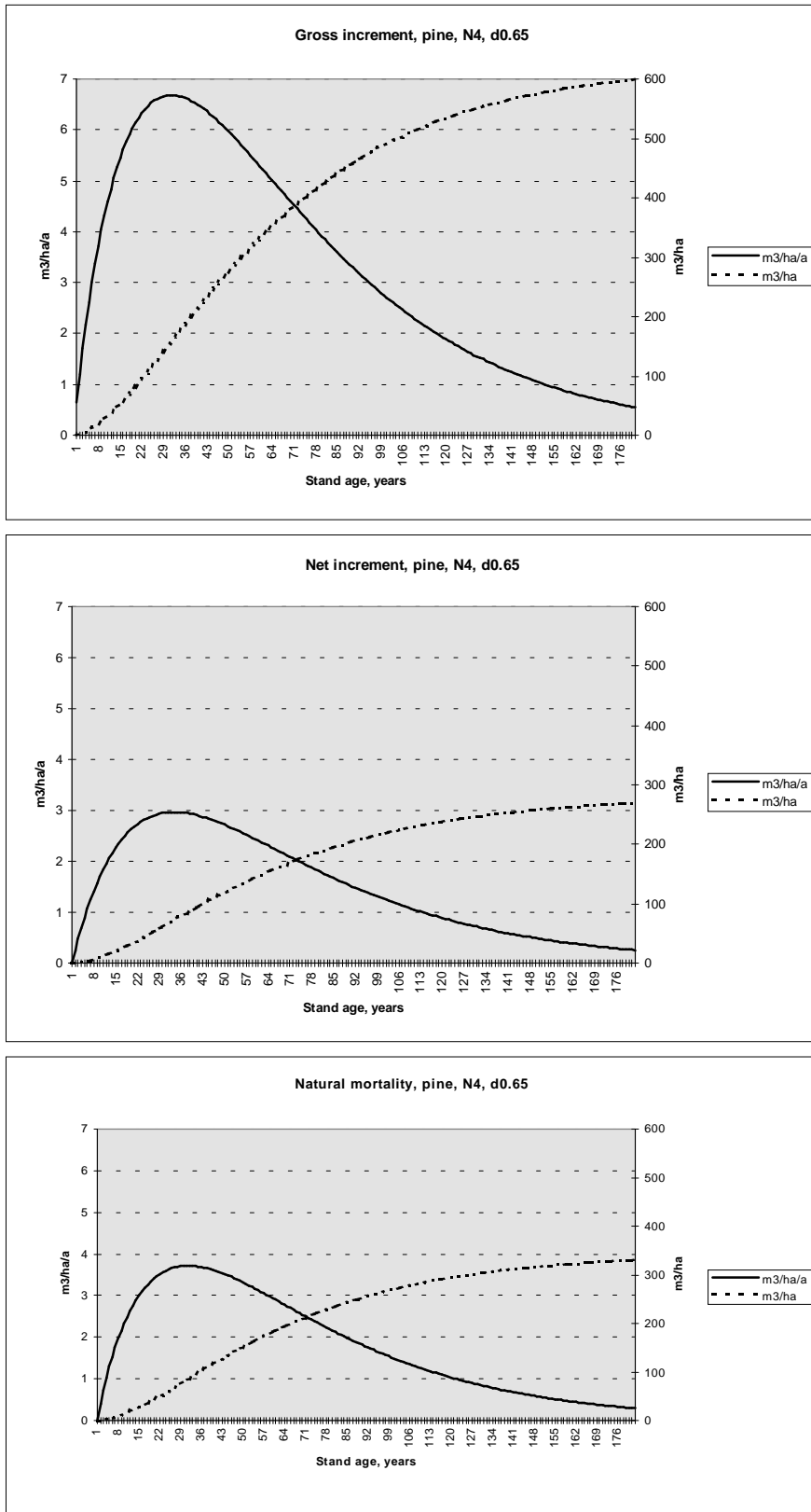
Figure 2. Development of yearly and accumulated gross production, net production and natural mortality for a pine stand on site index III and with a density of 0.65.
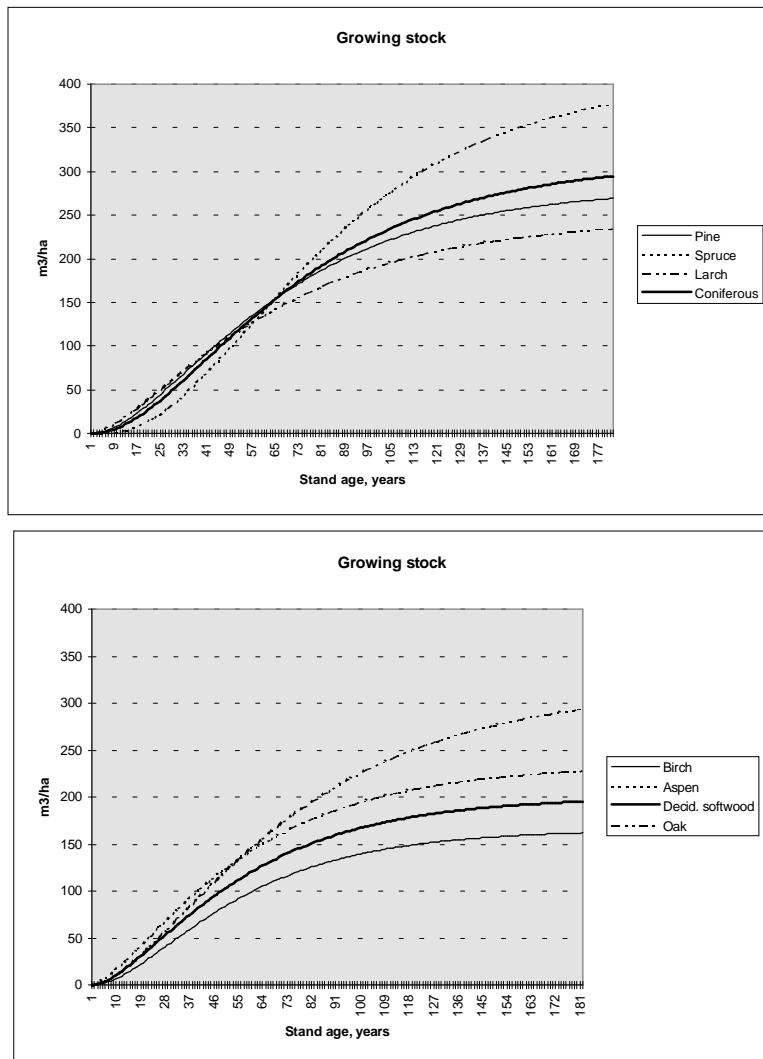
Figure 3. Development of the growing stemwood stock for different species stands on site index III and with a density 0.65. Coniferous represents an average for all coniferous species, and deciduous softwood represents an average of birch and aspen.

The actual harvesting varies each year and one possibility to generate this variation in harvesting is to use the annual allowable cut (AAC) * random number, which should be smaller than 1.0 but probably bigger than 0.2 - 0.4. For example in the Angara-Lena Southern Taiga ecoregion, which has been used as a test region, the actual harvesting in 1991 was 70% of the annual allowable cut for coniferous and 15% soft deciduous species.

The annual HARV can now be calculated for the coniferous group as aac-cw-con * random number between 0.7 and 1.0 (e.g. aac-cw-con/fh-cw-coni ±50%), for the hard deciduous group as aac-cw-har * random number between 0.2 and 0.5, and for the soft deciduous group as aac-cw-sof * random number between 0.2 and 0.5.

Another way to deal with the harvest in the simulations is to increase harvest by e.g. 1% for each year based on the initial level. This is assuming that the harvesting in

1990 was at the lowest level and will increase steadily in future. Harvesting could also be based on scenarios, if those would available.

The current version of the DIST calculations (crown fires) assumes that 20% of the biomass is burned (released into the atmosphere) and the remaining 80% is transformed to litter (Shvidenko *et al.* 1995). More precisely, 100% of the foliage biomass is burned, 50% of the branches, and the remaining 20% burned material is assumed to be stemwood. Only carbon is currently considered in the calculations (oxidation of carbon that is bound in the biomass), i.e. other greenhouse gases from the burning are not accounted for. A more detailed fire submodel can be incorporated later in the calculation model when more relevant information and knowledge on forest fire processes is available.

The annually burned area should represent the average burned area for several years, but there should also be some variations in the areas burnt similar to harvesting (mean + deviation*random number, calculated from the IIASA database). In this case a random number can be negative (burned areas are less than the average burned areas) or positive (burned areas are larger than average). The probability of forest fires can also be related to a summer temperature and precipitation relationship (a kind of dryness index), indicating that in some regions the probability of fire is higher than in other regions. The IIASA database also includes weather data and can support this type of index calculation.

3.4. Calculation of biomass allocation

The conversion of stem volume (V_{st}, m^3) to biomass components (M_{fr}, Mg) is made by a biomass ratio (R_{fr}, Mg/m^3):

$$M_{fr} = V_{st} \cdot R_{fr}$$

The biomass ratio can be calculated either with the help of Lakida *et al.* (1996) equations or with those of Shvidenko *et al.* (1996b). Since Shvidenko *et al.* equations are for Siberian forests, they are preferred. In some cases Lakida *et al.* equations have been used, although they are for the European part of Russia.

When growing stock (*GS)* is calculated, it has to be converted into biomass components (*fr*) of foliage (*f*), branches (*br*), coarse roots (*bl*), fine roots (*fbl*), stemwood (*st*), and understory (*us*, which consists of forest floor vegetation, undergrowth, and bushes) as

$$M_{fr} = GS_{st} \cdot R_{fr(..)}$$

Since neither of the allocation equations consider fine roots, it is assumed that fine-roots have about one third of the mass of foliage (Vanninen *et al.* 1996). Also annual growth (*dGS*), natural mortality (*dM*), harvesting (HARV) and disturbances (DIST) are converted into biomass components.

Three types of equations are given by Lakida *et al.* (1996):

(1) $R_{fr(..)} = a_0 \cdot A^{a_1} \cdot B^{a_2} \cdot e^{a_3 \cdot A}$

(2) $R_{fr(..)} = a_0 \cdot A^{a_1} \cdot B^{a_2}$

(3) $R_{fr(..)} = a_0 \cdot A^{a_1}$

where A is stand age, a_0, a_1, a_2, and a_3 are species specific coefficients, and B is height site index. Site index (*N*) can be transformed into height site index (Lakida *et al.* 1996) as

$B = 39 - 4 * N$

Lakida *et al.* (1996) equations are valid with the given coefficients for deciduous species from age 10 to 120, and for coniferous species from age 10 to 200. Equation (1) is to be used for all species and all components, except for pine roots and birch roots equation (2) should be employed, for aspen roots equation (3), and for understory equation (3) in aspen stands.

The preferred Shvidenko *et al.* (1996c) equation is:

$R_{fr} = (a_0 + a_1 \cdot A + a_2 \cdot A^2) \cdot A^{a_3} \cdot GS_{st}^{a_4}$

where A is stand age, a_0, a_1, a_2, a_3 and a_4 parameters (species and biomass fraction specifics, which are given in a separate file), and GS_{st} growing stemwood stock in m^3. Biomass for stemwood is calculated without bark, and therefore biomass fraction for bark ($R_{fr(ba)}$) has to be calculated too.

Tree species proportions calculated earlier are used as weights when calculating the coefficients. Allocation of the biomass in different species stands with both equations is shown in *Figures 4-10*.

Based on a comparison between Lakida *et al.* (1996) and Shvidenko *et al.* (1996c) equations, equations for different tree species and biomass components were selected (see Equation in Table 5). In cases where the Shvidenko *et al.* (1996c) equation did not describe dynamics satisfactorily, the Lakida *et al.* (1996) equation was used. In some cases other tree species parameters were used instead of using species specific parameters if the specific parameters behaved in a peculiar manner. These exceptions were:

- for pine branches, Shvidenko *et al.* equation but with larch parameters, since pine parameters gave too high biomass in the early development phase (see *Figure 4*),

- for spruce coarse roots, Lakida *et al.* equation, since specific parameters were not available for the Shvidenko *et al.* equation,

- for fir needles, Shvidenko *et al.* equation but with spruce parameters, since fir parameters gave too high biomass in the early development phase (see *Figure 6*),

- for fir coarse roots, Lakida *et al.* equation with spruce parameters, since no parameters were available for the Shvidenko *et al.* equation,

- for larch coarse roots, Lakida *et al.* equation, since no parameters were available for the Shvidenko *et al.* equation,

- for birch leaves, Lakida *et al.* equation, since Shvidenko *et al.* equation gave too high biomass in the early development phase (see *Figure 8*) and the Shvidenko *et al.* equation with aspen parameters behaved in a peculiar manner (see *Figure 9*),

- for birch coarse roots, Lakida *et al.* equation since no parameters were available for the Shvidenko *et al.* equation,

- for birch bark, Shvidenko *et al.* equation but with aspen parameters, since birch parameters gave too high biomass values and behaved in a peculiar manner (see *Figure 9*),

- for aspen leaves, Lakida *et al.* equation, since Shvidenko *et al.* equation with aspen parameters behaved in a peculiar manner (see *Figure 9*),

- for aspen coarse roots, Lakida *et al.* equation since no parameters were available for the Shvidenko *et al.* equation,

- for aspen branches, Shvidenko *et al.* equation but with birch parameters, since Shvidenko *et al.* equation with aspen parameters behaved in a peculiar manner (see *Figure 9*), and

- for aspen understory, birch understory parameters since no were parameters available for aspen.

At harvesting, part of the stemwood is left on site (ONSITE). Currently we assume 0.20 for ONSITE. The proportion of harvesting losses may be very significant, even 40% (Shvidenko and Nilsson 1994), and in Siberia maybe 50-60%. Nilsson *et al.* (1992) give 20% for wood waste of the harvested volume for European Russia. Other biomass components are assumed to be left on site as felling residues.

In the case of crown fire (DIST), 20% of the biomass is assumed to burn and 80% to die (Shvidenko *et al.* 1995). The proportion that dies has to be calculated separately, since it will be part of the litterfall. In the current calculations all the foliage, 50% of the branches, and a proportion of the stemwood are assumed to burn. The proportion of the burned material is estimated by:

$$b_{st} = \frac{0.2 \cdot GS_{tot} - 1.0 \cdot GS_f - 0.5 \cdot GS_{br}}{GS_{st}}$$

3.5. Calculation of litterfall

Total litterfall consists of annual litter from living trees, litter from dead trees (total biomass), and litter from harvesting and disturbances. The litterfall is calculated by employing the biomass components described earlier.

Table 5. Equations and parameters used for biomass allocation. Eq 1 refers to Shvidenko *et al.*, eq 2 to Lakida *et al.* equation 1, eq 3 to Lakida *et al.* equation 2. For gray and black alder, aspen parameters were used.

species	ratio	equation	a_0	a_1	a_2	a_3	a_4
pine	$R_{v(f)}$	1	2.4113	-0.0051	0.000021	-0.3853	-0.4898
	$R_{v(br)}$	1	0.0204	-0.00009	0.00000014	0.4057	-0.0693
	$R_{v(st)}$	1	0.353	0.0004	-0.000003	0.1283	-0.0838
	$R_{v(ba)}$	1	0.0343	-0.00017	0.0000003	0.59	-0.3541
	$R_{v(bl)}$	1	0.1005	0.0011	-0.000004	0.0734	-0.2148
	$R_{v(us)}$	2	217.7	-1.726	-0.999	0.023	
spruce	$R_{v(f)}$	1	252.9855	-2.4667	0.1519	-2.0635	-0.1441
	$R_{v(br)}$	1	0.3198	0.0056	-0.00001	-0.3872	-0.1156
	$R_{v(st)}$	1	1.5586	0.0223	-0.00005	-0.3495	-0.0723
	$R_{v(ba)}$	1	0.7596	0.0173	-0.00002	-0.5447	-0.2484
	$R_{v(bl)}$	2	3.017	-0.583	-0.324	0.005	
	$R_{v(us)}$	2	444000	-1.94	-3.398	0.02	
fir	$R_{v(f)}$	1	252.9855	-2.4667	0.1519	-2.0635	-0.1441
	$R_{v(br)}$	1	0.1081	-0.0002	0.000001	0.4254	-0.4642
	$R_{v(st)}$	1	0.5983	-0.0013	0.0000077	0.044	-0.1145
	$R_{v(ba)}$	1	0.0094	-0.0001	0.00000035	0.9621	-0.3062
	$R_{v(bl)}$	2	3.017	-0.583	-0.324	0.005	
	$R_{v(us)}$	2	444000	-1.94	-3.398	0.02	
larch	$R_{v(f)}$	1	0.0162	-0.00006	0.00000008	0.3216	-0.1759
	$R_{v(br)}$	1	0.0204	-0.00009	0.00000014	0.4057	-0.0693
	$R_{v(st)}$	1	0.3306	-0.0003	0.0000005	0.0993	0.0286
	$R_{v(ba)}$	1	0.5375	0.0265	-0.00004	-0.6331	-0.0764
	$R_{v(bl)}$	1	0.1005	0.0011	-0.000004	0.0734	-0.2148

	$R_{v(us)}$	2	217.7	-1.726	-0.999	0.023	
oak	$R_{v(f)}$	2	102.5	-1.286	-1.256	0.01	
	$R_{v(br)}$	2	111.4	-0.378	-1.631	0.002	
	$R_{v(st)}$	2	0.629	-0.049	-0.006	0.002	
	$R_{v(bl)}$	2	0.027	-1.379	1.736	0.023	
	$R_{v(us)}$	2	0.000427	4.137	-2.91	-0.058	
birch	$R_{v(f)}$	2	110	-1.348	-1.356	0.014	
	$R_{v(br)}$	1	1.9818	-0.0145	0.0012	-0.8689	-0.048
	$R_{v(st)}$	1	-4.33	1.2763	0.0081	-1.356	0.0643
	$R_{v(ba)}$	1	0.187	-0.0024	0.000018	-0.1576	-0.0337
	$R_{v(bl)}$	3	0.694	-0.063	-0.272		
	$R_{v(us)}$	2	415.7	0.116	-2.61	-0.025	
aspen	$R_{v(f)}$	2	110	-1.348	-1.356	0.014	
	$R_{v(br)}$	1	1.9818	-0.0145	0.0012	-0.8689	-0.048
	$R_{v(st)}$	1	0.4453	-0.0026	0.000017	0.2926	-0.1491
	$R_{v(ba)}$	1	0.187	-0.0024	0.000018	-0.1576	-0.0337
	$R_{v(bl)}$	3	0.694	-0.063	-0.272		
	$R_{v(us)}$	2	415.7	0.116	-2.61	-0.025	
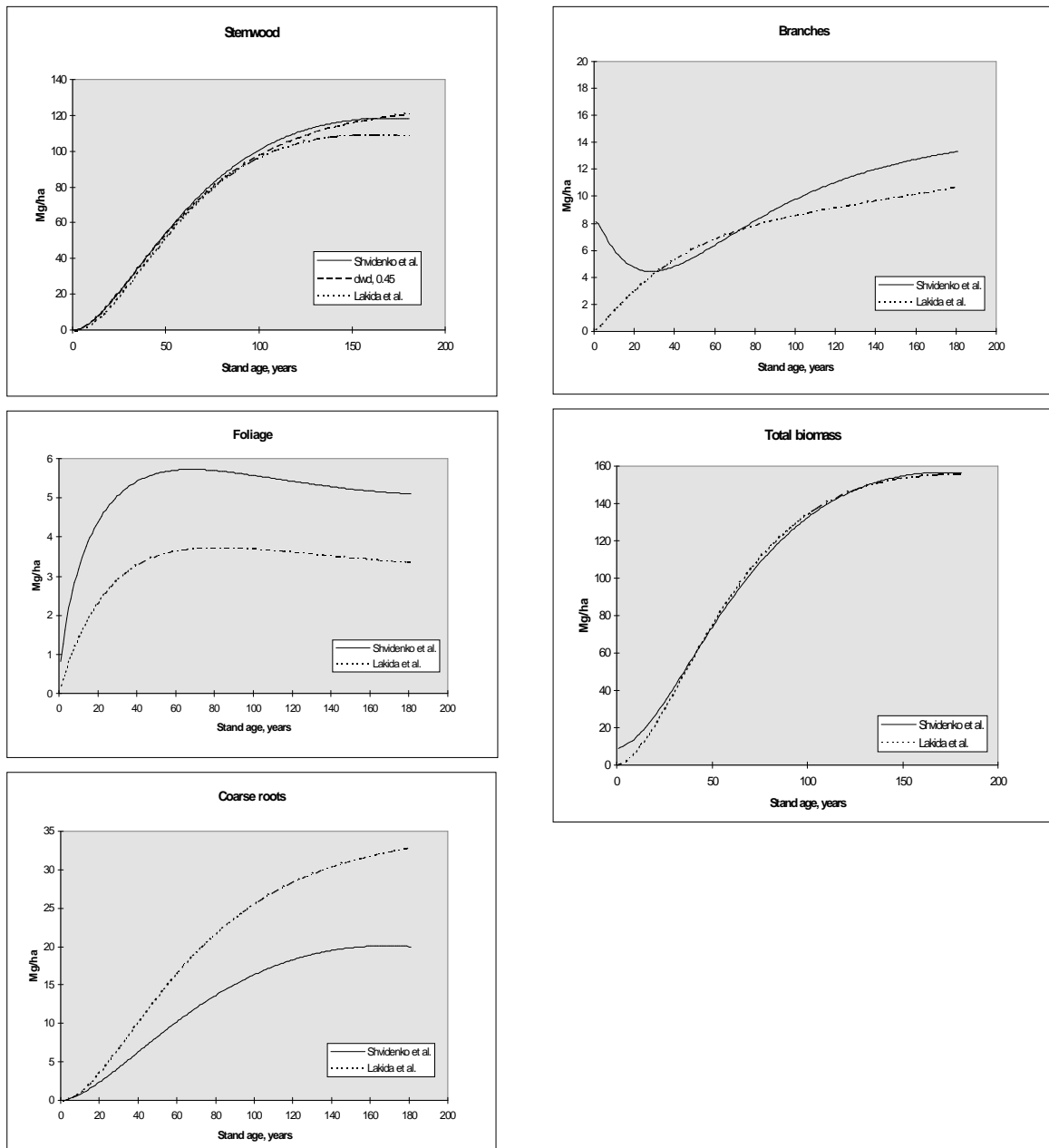
Figure 4. Development of biomass in a pine stand (see *Figure 3*) based on Lakida *et al.* (1996) and Shvidenko *et al.* (1996c) equations. In Shvidenko *et al.* Middle taiga parameters have been applied. Stemwood biomass has been calculated by comparisons based on dry weight densities.
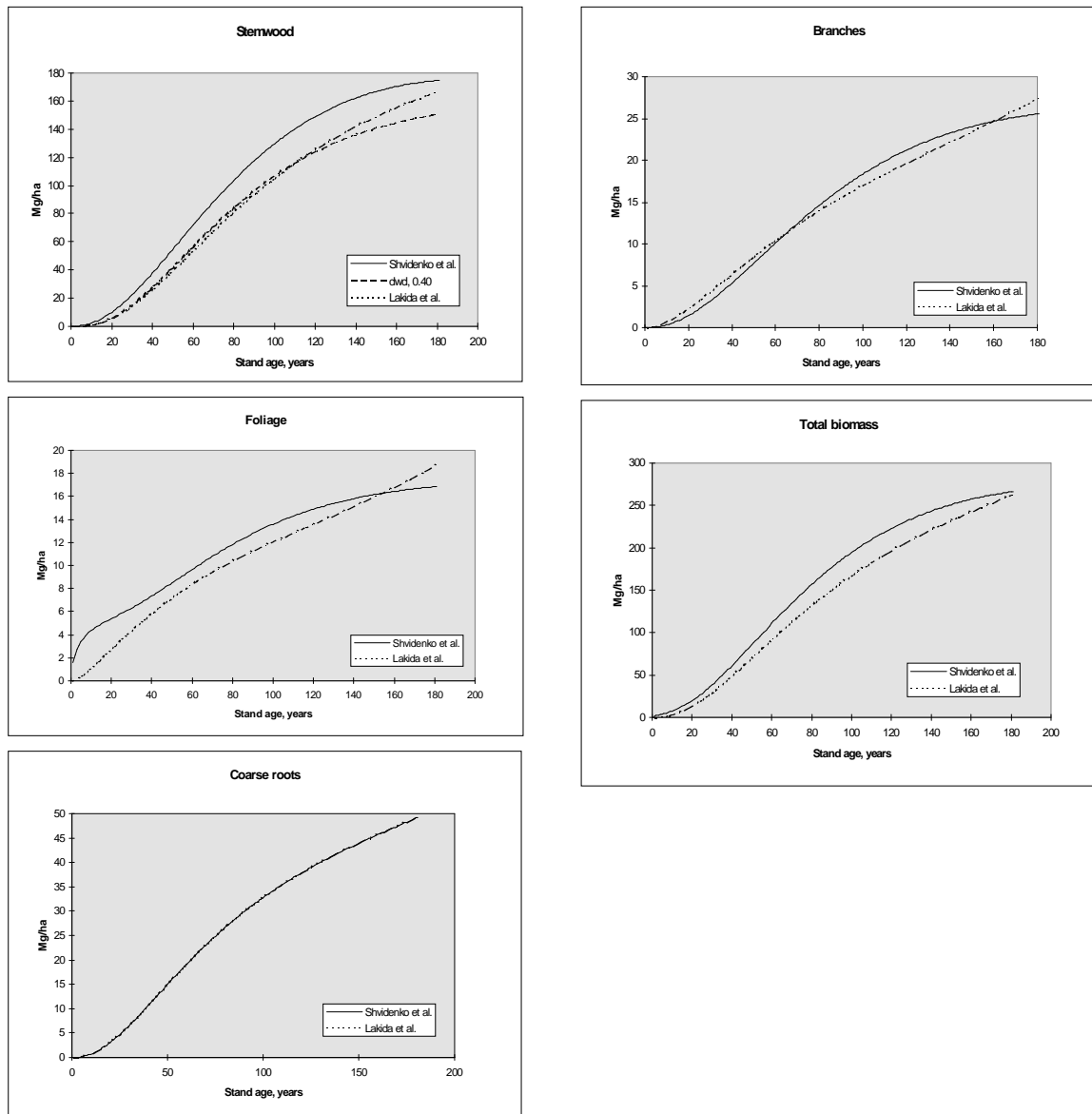
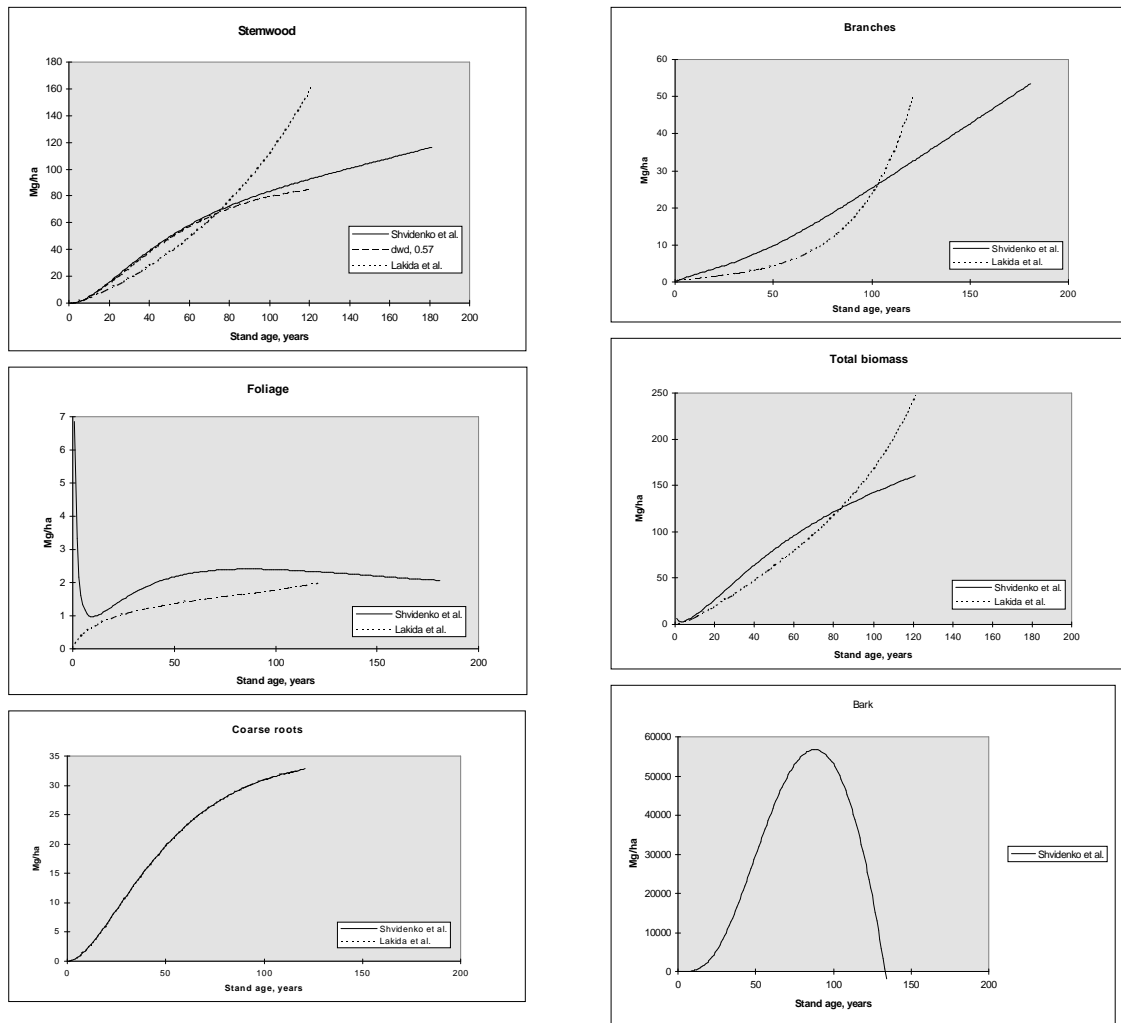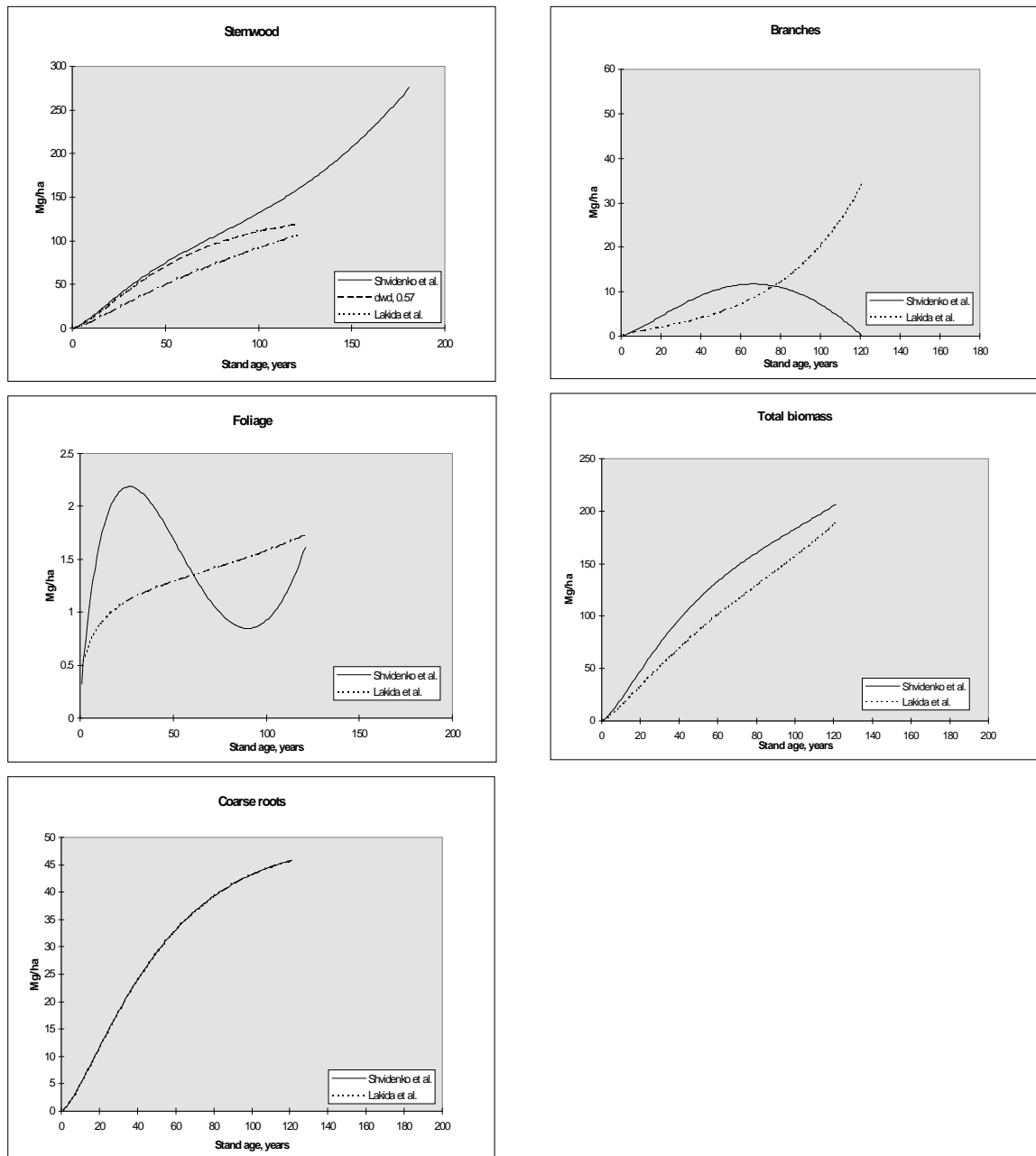**Figure 5.** Development of biomass in a spruce stand (see *Figure 3*) based on Lakida *et al.* (1996) and Shvidenko *et al.* (1996c) equations. Coarse roots estimates are based on Lakida *et al.* Stemwood biomass has been calculated by comparisons based on dry weight densities.
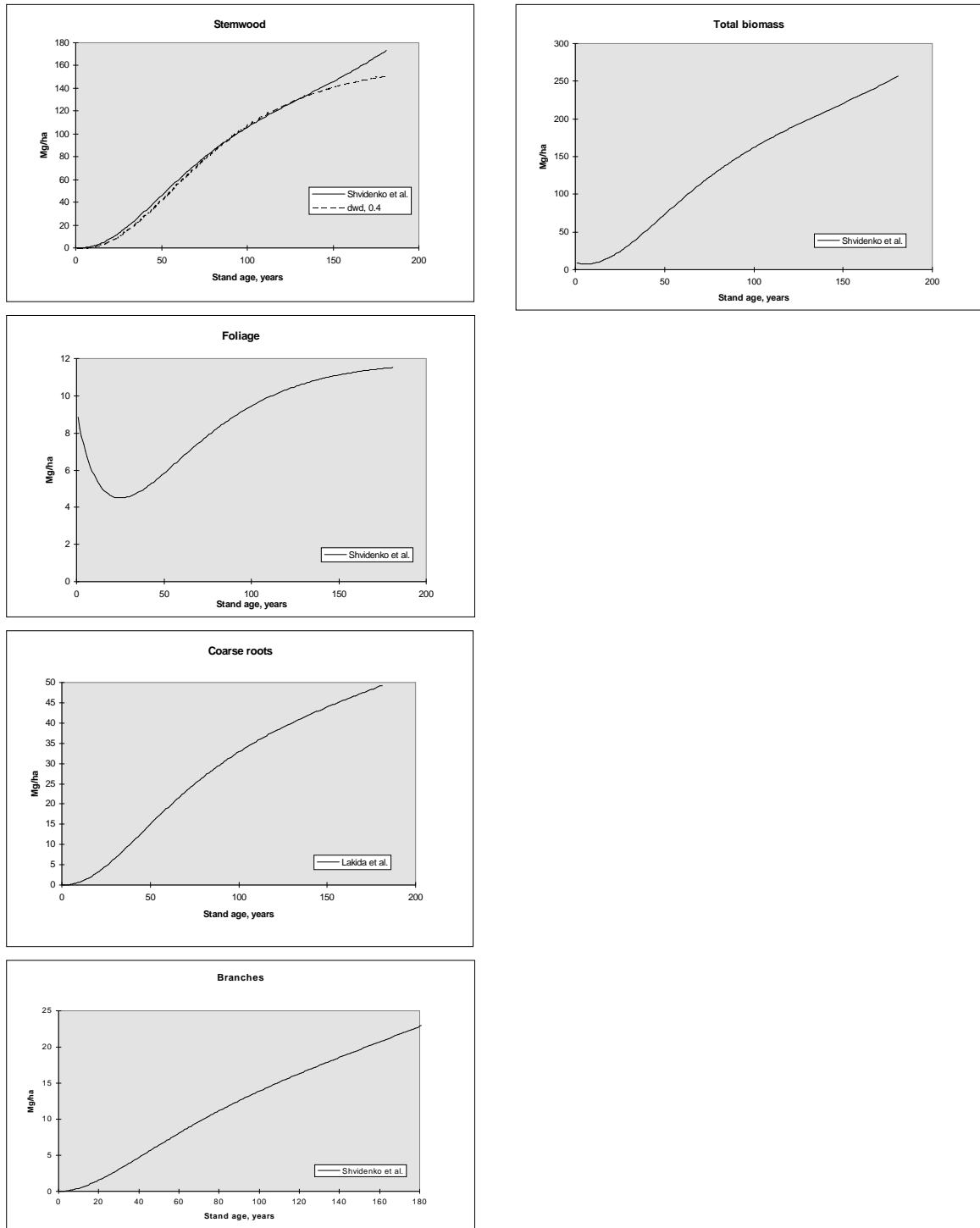
Figure 6. Development of biomass in a fir stand (see *Figure 3*, spruce) based on Shvidenko *et al.* (1996c) equations. Coarse roots estimates are based on Lakida *et al.* (1996). Stemwood biomass has been calculated by comparisons based on dry weight densities.
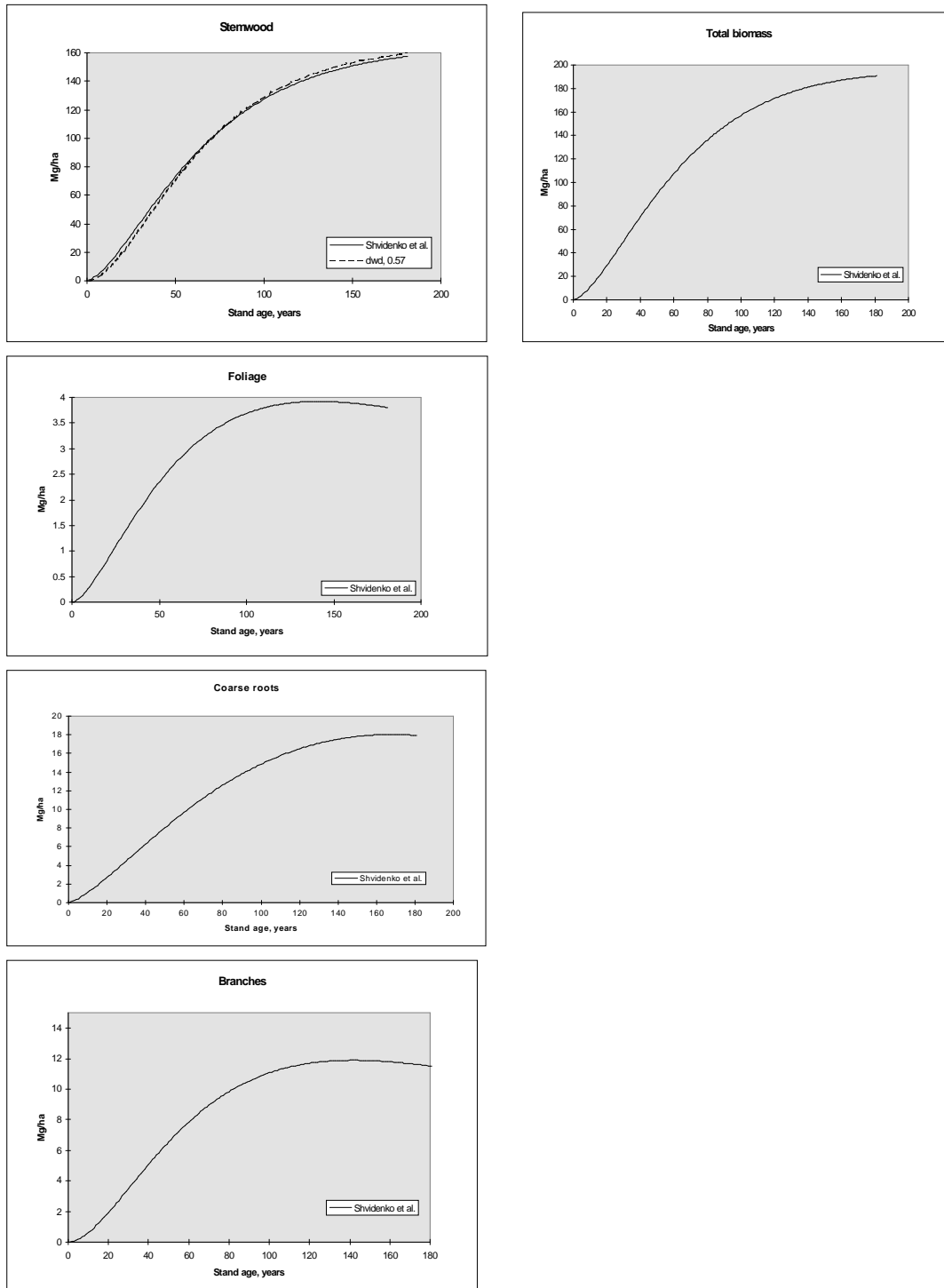
Figure 7. Development of biomass in a larch stand (see *Figure 3*) based on Shvidenko *et al.* (1996c) equations. For coarse roots estimates, pine parameters have been used. Stemwood biomass has been calculated by comparisons based on dry weight densities.
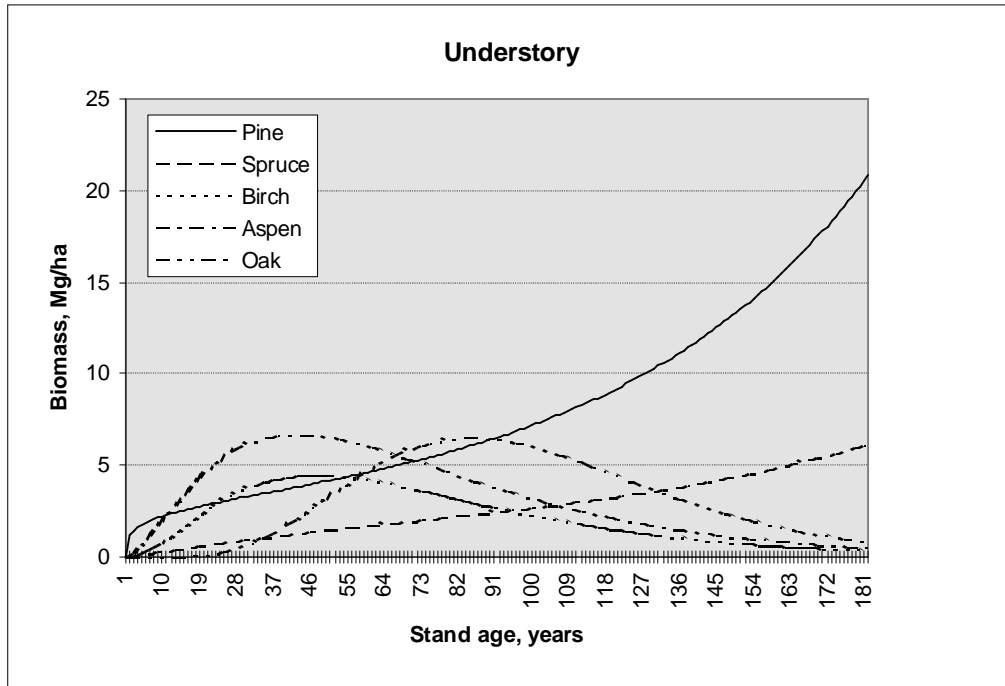
Figure 8. Development of biomass in a birch stand (see *Figure 3*) based on Lakida *et al.* (1996) and Shvidenko *et al.* (1996c) equations. For coarse roots estimate, Lakida *et al.* have been applied, and for bark aspen parameters have been used instead of the birch estimate shown in the figure. Stemwood biomass has been calculated by comparisons based on dry weight densities.

Figure 9. Development of biomass in a aspen stand (see *Figure 3*) based on Lakida *et al.* (1996) and Shvidenko *et al.* (1996c) equations. For coarse roots estimates, Lakida *et al.* have been applied. Stemwood biomass has been calculated by comparisons based on dry weight densities.

Figure 10. Development of the understory biomass (forest floor vegetation, undergrowth, and bushes) based on Lakida *et al.* (1996) equations for different species stands (see *Figure 3*). For aspen stands birch stand parameters have been used.

To calculate the annual litterfall, turnover times (TURNOV) have been applied for biomass components other than stemwood, i.e. a certain proportion of the biomass is supposed to fall each year as litter to the ground in the form of biomass. The TURNOV times expressed in years employed in the calculations are presented in the following:

<div align="center">

TURNOV

</div>

foliage[1]	
- deciduous	1
- larch	1
- pine	5
- spruce	9
fineroots[2]	1
coarse roots[3]	50
branches[4]	80
understory	
- in deciduous stands	3
- in coniferous stands	3+0.0389*A, where A is stand age

[1] Nilsson 1971, Mälkönen 1974, Flower-Ellis and Mao-Sheng 1987
[2] Persson 1983
[3] Mälkönen 1974

TURNOV for understory in coniferous stands is calculated in a different way than in deciduous stands (see above). A fixed proportion produces an exceptionally high amount of litter in coniferous stands, therefore litter production is related to the stand age. This is based on the assumption that in coniferous stands the understory consists of longer living species than in deciduous stands, i.e. the proportion of scrubs is

larger. For fir we used the TURNOV of spruce, and for cedar that of pine.

The total litter production for each biomass component is calculated then as

$$LITT_{st(year)} = dM_{year} + HARV \cdot ONSITE + (1 - b_{st} \cdot DIST)$$

$$LITT_{br(year)} = dM_{year} \cdot Rv_{(br)} + HARV \cdot Rv_{(br)} + (1 - b_{br}) \cdot DIST \cdot Rv_{(br)} + GS_{br(year)} / TURNOV_{br}$$

$$LITT_{f(year)} = dM_{year} \cdot Rv_{(f)} + HARV \cdot Rv_{(f)} + (1 - b_f) \cdot DIST \cdot Rv_{(f)} + GS_{f(year)} / TURNOV_f$$

$$LITT_{bl(year)} = dM_{year} \cdot Rv_{(bl)} + HARV \cdot Rv_{(bl)} + (1 - b_{bl}) \cdot DIST \cdot Rv_{(bl)} + GS_{bl(year)} / TURNOV_{bl}$$

$$LITT_{fbl(year)} = dM_{year} \cdot Rv_{(fbl)} + HARV \cdot Rv_{(fbl)} + (1 - b_{fbl}) \cdot DIST \cdot Rv_{(fbl)} + GS_{fbl(year)} / TURNOV_{fbl}$$

$$LITT_{us(year)} = HARV \cdot Rv_{(us)} + (1 - b_{us}) \cdot DIST \cdot Rv_{(us)} + GS_{us(year)} / TURNOV_{us}$$

Litter that originates from crown fire (DIST), is currently assumed to come to 80% from the biomass (Shvidenko *et al.* 1995). The proportion that burns is coefficient *b* in the above equations. Current values for the coefficient are (see section 3.3. for the description of the disturbance calculation):

$b_f = 1.0$

$b_{br} = 0.5$

$b_{st} = \frac{0.2 \cdot GS_{tot} - b_f \cdot GS_f - b_{br} \cdot GS_{br}}{GS_{st}}$

$b_{bl} = 0$

$b_{fbl} = 0$

$b_{us} = 0$

HARV is the amount of stemwood that is harvested. Due to harvesting and disturbances, all the understory is transferred into litter.

3.6. Calculation of the carbon budget

Total production (TOTP) and net production (NETP) of the vegetation have to be calculated in order to estimate the vegetation carbon budget, also biomass has to be converted into carbon. To convert biomass to carbon a factor (cf) of 0.5 is used.

NETP for each biomass component (*st, f, br, bl, fbl, us*) is the annual biomass increment of the biomass component ($\Delta GS = GS\text{-}year+1 - GS\text{-}year$), and the cumulative value gives the amount of biomass, taking into account harvesting and disturbances.

TOTP for each biomass component (*st, f, br, bl, fbl, us*) is NETP(*st, f, br, bl, fbl, us*) + DIST(*st, f, br, bl, fbl, us*) + HARV(*st, f, br, bl, fbl*) + NATURAL-MORTALITY(*st, f, br, bl, fbl*) + ANNUAL-LITTER(*f, br, bl, fbl, us*) (*Figure 11*).
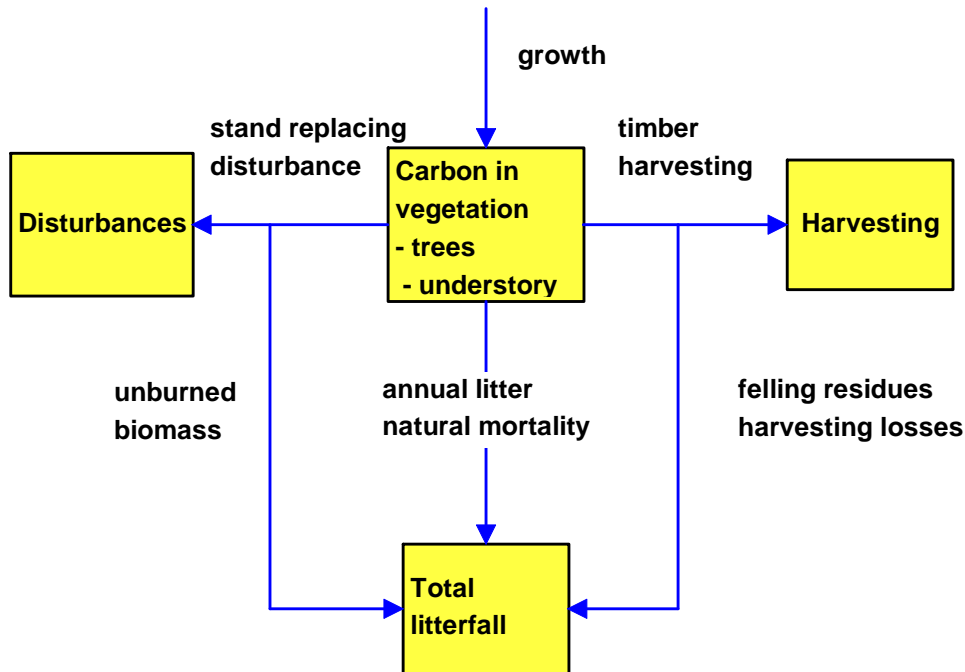

Figure 11. Outline of the vegetation carbon budget calculation.

DIST is the amount of biomass affected by stand replacing disturbances that is not included in NATURAL-MORTALITY, broken down to biomass components. HARV is the amount of biomass removed from forest due to harvesting, including stemwood left on the sites as harvesting waste, broken down to biomass components. NATURAL-MORTALITY is the amount of biomass calculated with the equation dM. ANNUAL-LITTER is part of the total litter production coming from the living vegetation.

The carbon budget is presented at ecoregional level by species group and total. Carbon storage of the living biomass is presented by components and total (*fGS, brGS, stGS, blGS, fblGS, usGS, totGS*). Annual carbon fluxes are for total production, net production, natural mortality, annual litter, harvest and disturbance (*dTOTP, dNETP, dNATURAL-MORTALITY, dANNUAL-LITTER, dHARV, dDIST*). Total annual litter (*dLITT*) by component is used as input to the soil carbon budget calculations (Liski 1997).

4. Preliminary calculations

4.1. Dynamics at stand level

Carbon dynamics was first computed at stand level. As an example a pine stand on site index III(N=4), and with a density of 0.65 (65% of the full stocking) was selected. The total production during a 180 year period is 719 Mg C/ha, the litterfall is 630 Mg C/ha, and the stock at the end of the period is 89 Mg C/ha (*Table 6*). The proportion of stemwood of the tree biomass at the end is 75%, that of roots 14%, branches 8%, and foliage 3%. Understory contained 11% of the vegetation carbon pool. Stemwood growth was 26% of the total production, fineroot production was 24%, formation of foliage 21%, growth of understory 16%, growth of coarse roots 9%, and growth of branches 4%. The dynamics are presented in *Figures 12-14*.
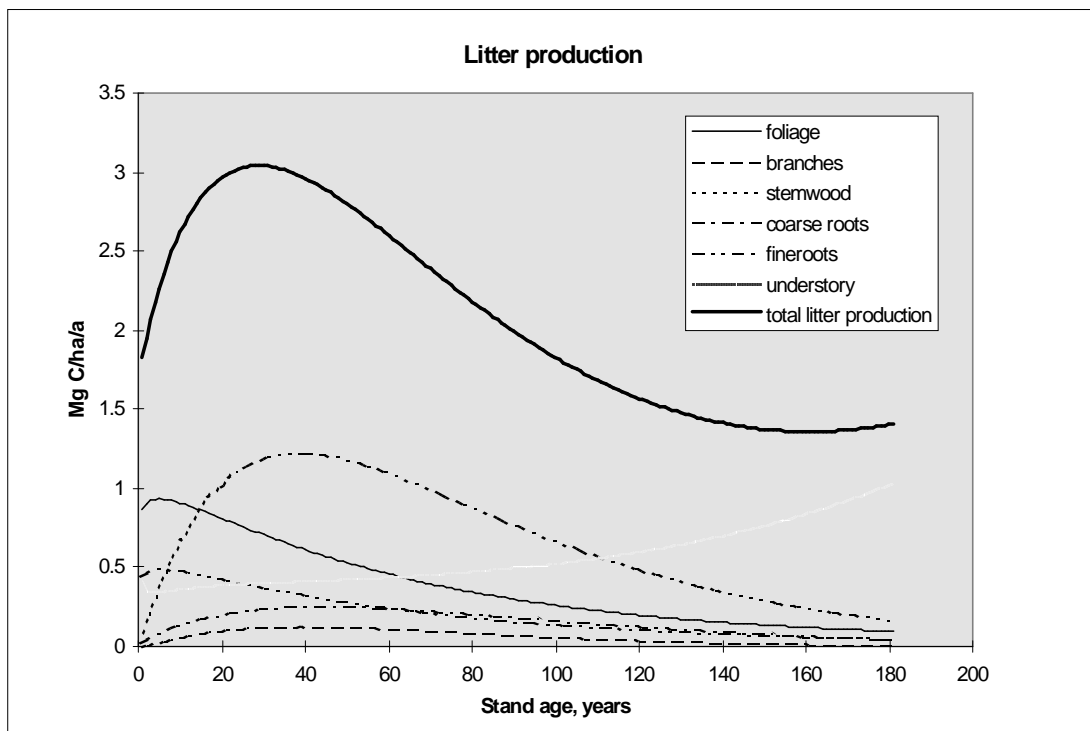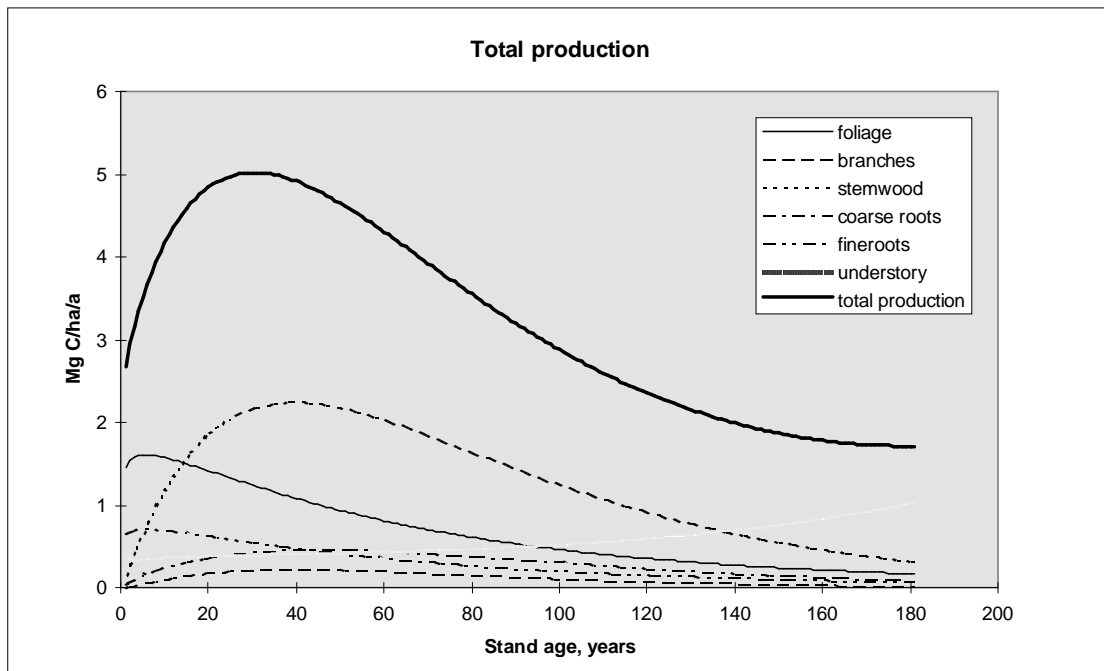
Figure 12. Dynamics of total production and litter production in a pine stand on site index III and with a density of 0.65.
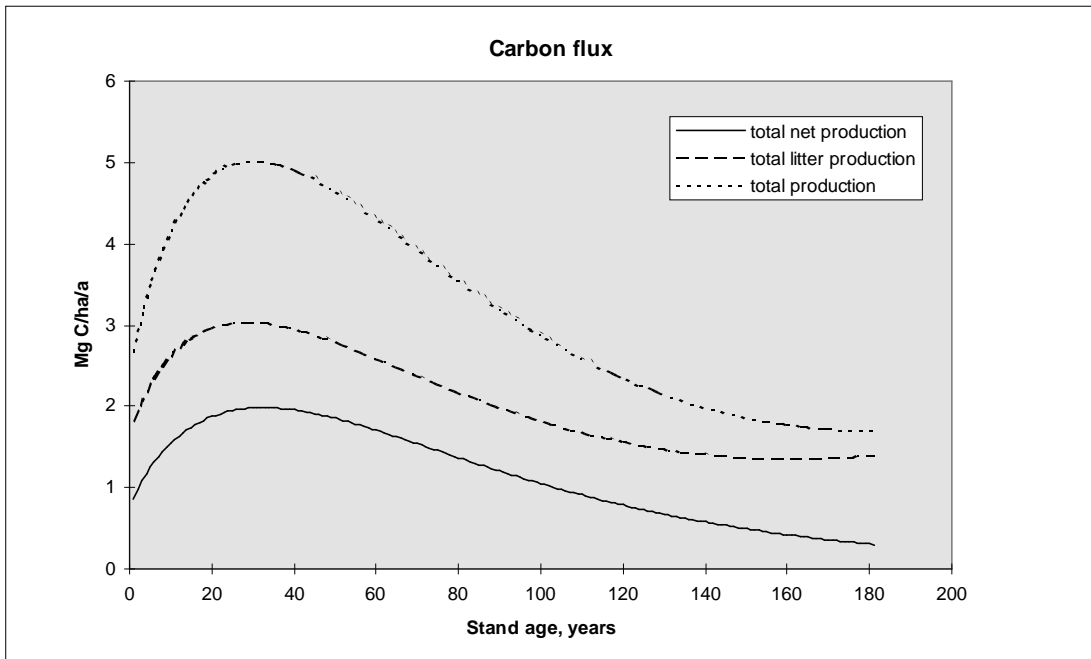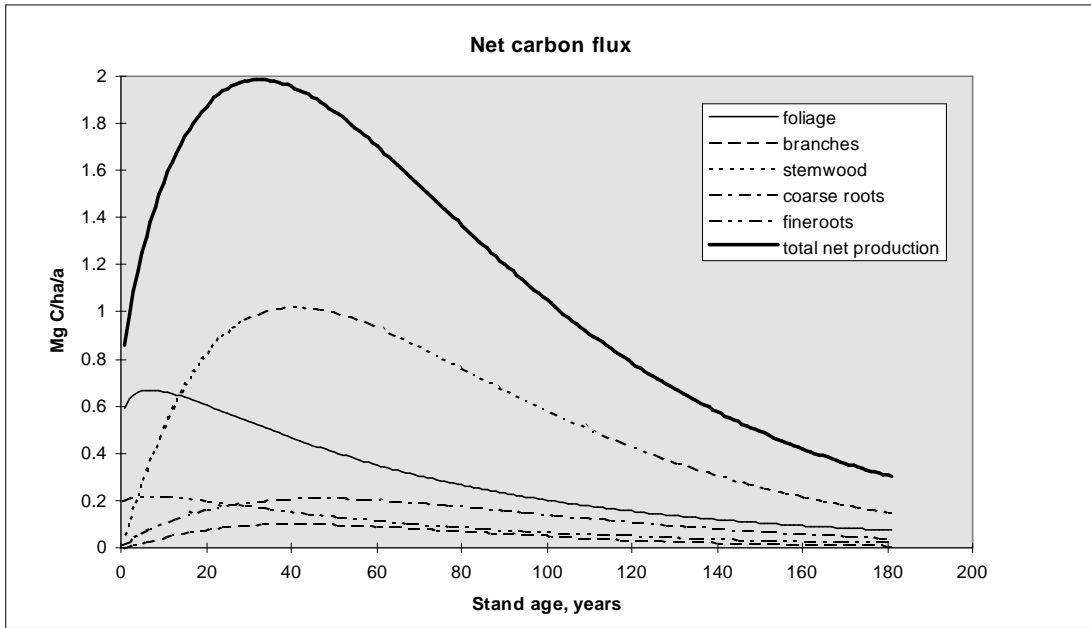
Figure 13. Dynamics of net production and total fluxes in a pine stand on site index III and with a density of 0.65.
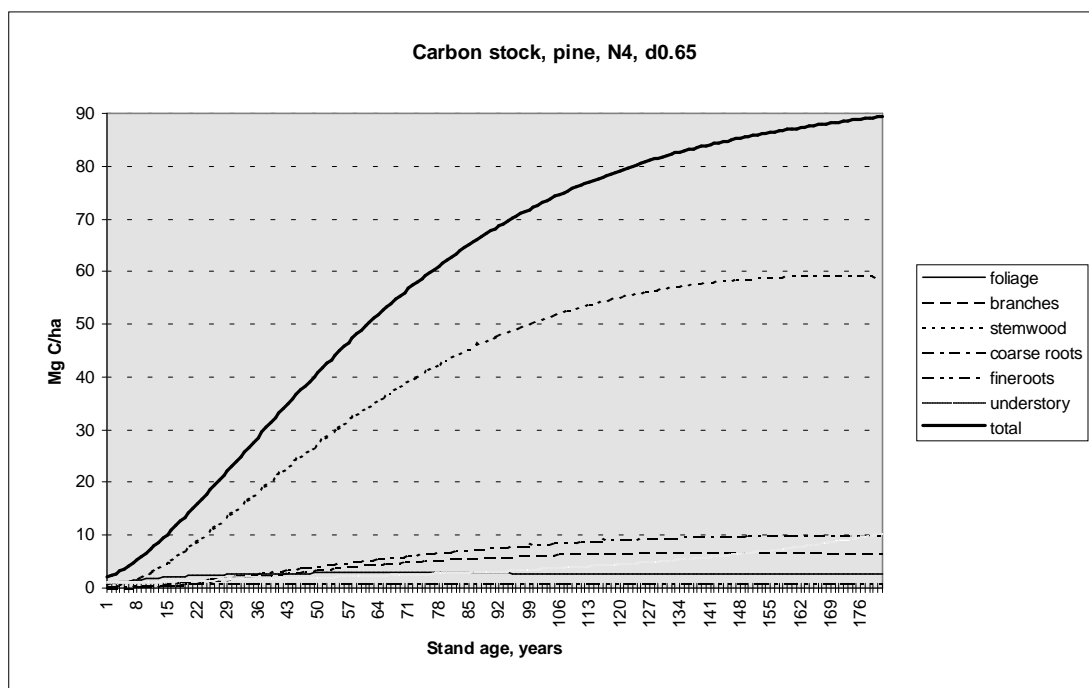
Figure 14. Dynamics of carbon stock components in a pine stand on site index III and with a density of 0.65.

Table 6. Total production and litter production during a 180 year period, and biomass at the end of the period for the test stand (pine stand on site index III and with a density of 0.65).

Mg C/ha	Total production	Annual litter	Natural mortality	Total litter	Biomass at the end of the period
foliage	154.7	93.6	58.6	152.2	2.6
branches	29.0	10.8	11.7	22.4	6.5
stemwood	183.9		124.9	124.9	59.0
coarse roots	61.7	23.7	28.0	51.7	10.0
fineroots	176.3	155.9	19.5	175.5	0.9
understory	113.3	102.9		102.9	10.4
total	719.0	386.9	242.7	629.6	89.4

In a birch stand on site index III and with a density 0.65, the total production is 367 Mg C/ha, and the total litter production is 286 Mg C/ha during a 120 year period. The tree biomass carbon pool at the end of the period is 80.6 Mg C/ha and in the understory pool 0.7 Mg C/ha.

The average annual total production during the 180 year period in the pine stand is 4.0 Mg C/ha/a, and the net production 0.5 Mg C/ha/a (*Table 7*). In the birch stand the total production during the 120 year period is 3.1 Mg C/ha/a, and the net production is 0.7 Mg C/ha/a.

Table 7. Average annual flows during a 180 year period for the test stand of pine on site index III, with a density of 0.65.

Mg C/ha/a	Total production	Annual litter	Natural mortality	Total litter	Net production
foliage	0.86	0.52	0.33	0.85	0.01
branches	0.16	0.06	0.07	0.13	0.03
stemwood	1.02		0.69	0.69	0.33
coarse roots	0.34	0.13	0.16	0.29	0.06
fineroots	0.98	0.87	0.11	0.98	0.01
understory	0.63	0.57		0.57	0.06
total	3.99	2.15	1.35	3.50	0.50

Simulations with a gap-type model for southern Finland conditions in pine stands (mean annual temperature $+4.0^{\circ}$C, precipitation 548 mm, heat sum 1330 d.d.) produced a net sequestration of 0.6 Mg C/ha/a in vegetation over a 200 year period, 1.9 Mg C/ha/a total litter and 2.6Mg C/ha/a of total production (Karjalainen 1996b). For northern Finland conditions (mean annual temperature $+0.5^{\circ}$C, precipitation 591 mm, heat sum 930 d.d.), the corresponding values were 0.5, 1.7 and 2.3 Mg C/ha/a, respectively. For birch stands in southern Finland, the net sequestration of vegetation was 0.5 Mg C/ha/a, total litter 3.9 Mg C/ha/a, and total production 4.4 Mg C/ha/a during a 200 year period. These net vegetation production figures are close to those achieved in this study.

Mälkönen (1974) studied primary production in Scots pine stands in Finland. These results and those of this study correlate quite well (*Table 8*). The largest difference is in the amount of stemwood and roots. In the simulation study by Karjalainen above (1996b), the total production at the same stand age was 3.5 Mg C/ha, the total litter production 2.8 Mg C/ha, and the net production 0.7 Mg C/ha. In the simulation study the maximum growth was reached earlier than in this study, which explains the differences in total production and net production.

Table 8. Total production, litter production, net production and stock of carbon in a pine stand with a stand age of 45 years in this study and in the Mälkönen (1974) study.

Mg C/ha	Total production		Total litter production		Net production		Stock	
	This study	Mälkönen	This study	Mälkönen	This study	Mälkönen	This study	Mälkönen
foliage	1.01	0.87	0.57	0.55	0.44	0.32	2.79	2.22
branches	0.23	0.44	0.13	0.27	0.10	0.17	3.02	5.30
stemwood	2.23	1.24	1.21		1.02	1.24	24.17	30.45
coarse roots	0.46	0.65	0.25	0.17	0.21	0.48	3.68	9.64
fineroots	0.45		0.31		0.15		0.93	
understory	0.42	1.02	0.42	1.02			2.01	2.75
total	4.80	4.21	2.89	2.01	1.91	2.20	36.60	50.34

4.2. Dynamics at ecoregional level

As a test region, Angara-Lena Southern Taiga ecoregion (location, north longitude 103-00, north latitude 59-19, east longitude 111-43, east latitude 58-39, south longitude 106-09, south latitude 52-32, west longitude 97-20, west latitude 57-02, in degrees and minutes) was selected. The annual average precipitation in this ecoregion is 425 mm. Although mean annual temperature in this region is -3.9°C, the summers are warm, since the sum of the degree days (threshold +5°C) is 1660, implying good conditions for forest growth.

The total area of the ecoregion is 29.0 million ha, of which 23.8 million ha are classified as forest land. Most of the forest land belongs to forest group III, 79% (*Table 9*). Only 2% belongs to forest group II, and forest group I constitutes 19%. Approximately 80% of the forest land is dominated by coniferous species, with some 88% of the 4596 million m^3 of growing stock. The proportion of mature and overmature stands is large, approximately 50% of the coniferous-dominated forested areas (closed forests), and 40% of the deciduous-dominated area belong to this class. Approximately 75% of the forest land is classified as exploitable.

Table 9. Forest land area and growing stock in the Angara-Lena Southern Taiga ecoregion in different forest groups. Areas are in 100 ha and volumes in 10000 m³. Source IIASA database.

Forest group	Species	Forest land	Mature and over-mature	%	Grow-ing stock	Mature and over-mature	%	Volume, m³/ha	Mature and over-mature
I, II, III	conif.	192069	99955	52	404834	249648	62	211	250
I, II, III	decid.	46210	17553	38	54802	34354	63	119	196
sum		238279	117508	49	459636	284002	62	193	242
I	conif.	40377	19572	48	89585	50401	56	222	258
I	decid.	5744	1484	26	5754	2775	48	100	187
sum		46121	21056	46	95339	53176	56	207	253
II	conif.	3178	1404	44	5386	3412	63	169	243
II	decid.	2087	666	32	2379	1339	56	114	201
sum		5265	2070	39	7765	4751	61	147	230
III	conif.	148514	78979	53	309863	195835	63	209	248
III	decid.	38379	15403	40	46669	30240	65	122	196
sum		186893	94382	51	356532	226075	63	191	240
exploitable	conif.	135269	80134	59	287499	202143	70	213	252
exploitable	decid.	40745	16454	40	50680	32627	64	124	198
sum		176014	96588	55	338179	234770	69	192	243

The structure of coniferous stands is rather uneven. Approximately 50% of the pine stands are evenaged, 35% relatively unevenaged, and 15% unevenaged. Spruce stands are even more unevenaged, since only 5% are evenaged, 25% relatively unevenaged, 30% unevenaged, and 40% gradually unevenaged. Only 10% of larch stands are evenaged, 75% are relatively unevenaged, and 15% are unevenaged. Approximately 10% of the cedar stands are evenaged, 15% relatively unevenaged, 30% unevenaged, and 45% gradually unevenaged. Most of the birch stands are evenaged, 70%, and 30% are relatively unevenaged.

The final harvest in 1991 was 21.7 million m³ of coniferous wood and 1.9 million m³ soft deciduous species, which correspond to 70% and 15% of the annual allowable cut, respectively.

Forest fire statistics show that 1990 was a bad fire year, 191000 ha burned, of which 76000 ha were crown fires. In 1989 the burned area was 13000 ha, and in 1991 21000 ha.

Preliminary simulations for the Angara-Lena Southern Taiga ecoregion, without stand replacing disturbances and without harvesting, show an increased growing stock from

the initial 4596.4 million m^3 (193 m^3/ha) to 6425.3 million m^3 (270 m^3/ha) within 110 years (*Figure 15*). Since a large proportion of the stands are mature or overmature at the beginning of the simulation, growth decreases over time (*Figure 16*). At the beginning of the simulation the total stemwood production is 61.9 million m^3/a (2.6 m^3/ha/a), the natural mortality 30.7 million m^3/a and the net increment 31.1 million m^3/a (1.3 m^3/ha/a). After 110 years simulation, the total stemwood production is only 10.1 million m^3/a (0.4 m^3/ha/a), natural mortality 4.7 million m^3/a and net increment 5.4 million m^3/a (0.2 m^3/ha/a).

The total biomass at the beginning of the simulation is 3653 Tg in dry weight (153 Mg/ha) of which 59% is stemwood (*Figure 17*). At the end, after the simulation the biomass increased to 5508 Tg (231 Mg /ha), of which 52% is stemwood. Litter production is 7.5 Mg/ha/a at the beginning, but increased to 9.0 Mg/ha/a due to increased litterfall from understory vegetation.

Standing stemwood stock

Average standing stemwood stock
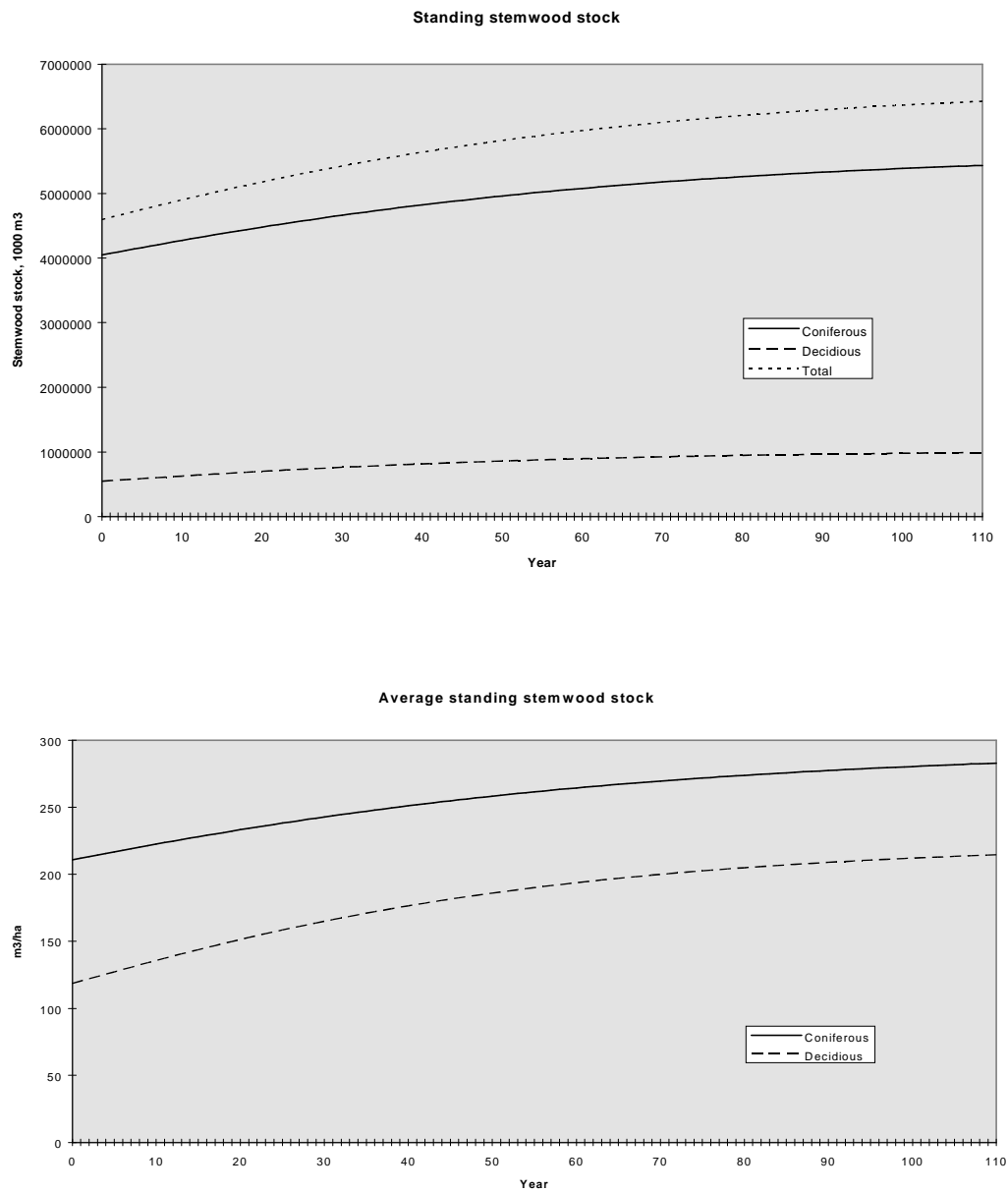
Figure 15. Development of growing stock in the Angara-Lena Southern Taiga ecoregion excluding stand replacing disturbances and harvesting.

Stemwood production
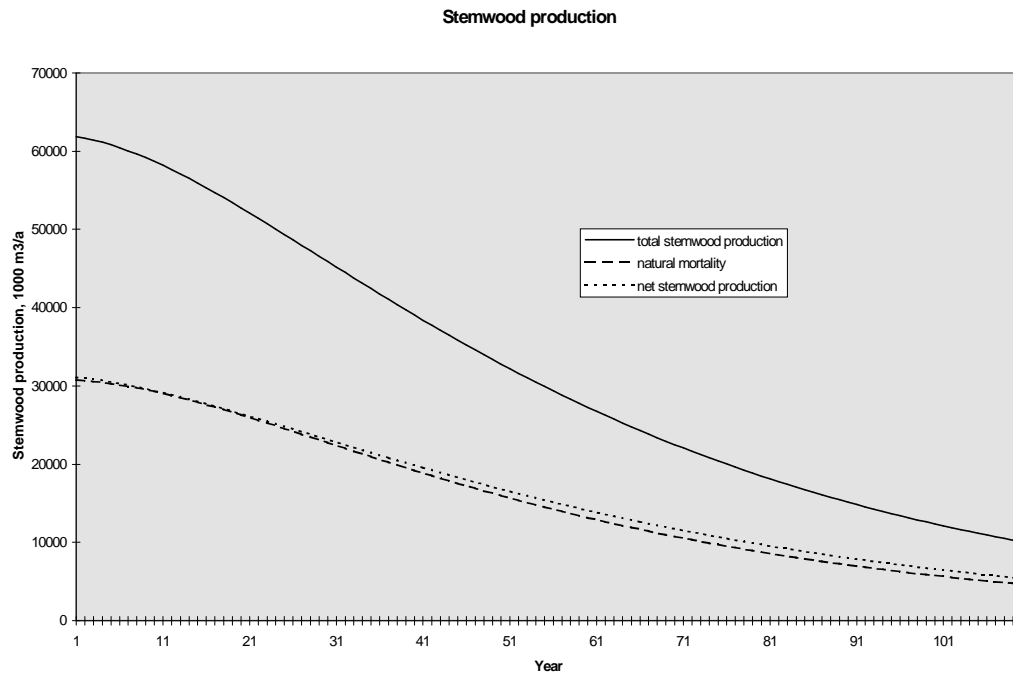
Figure 16. Development of stemwood production in the Angara-Lena Southern Taiga ecoregion excluding stand replacing disturbances and harvesting.
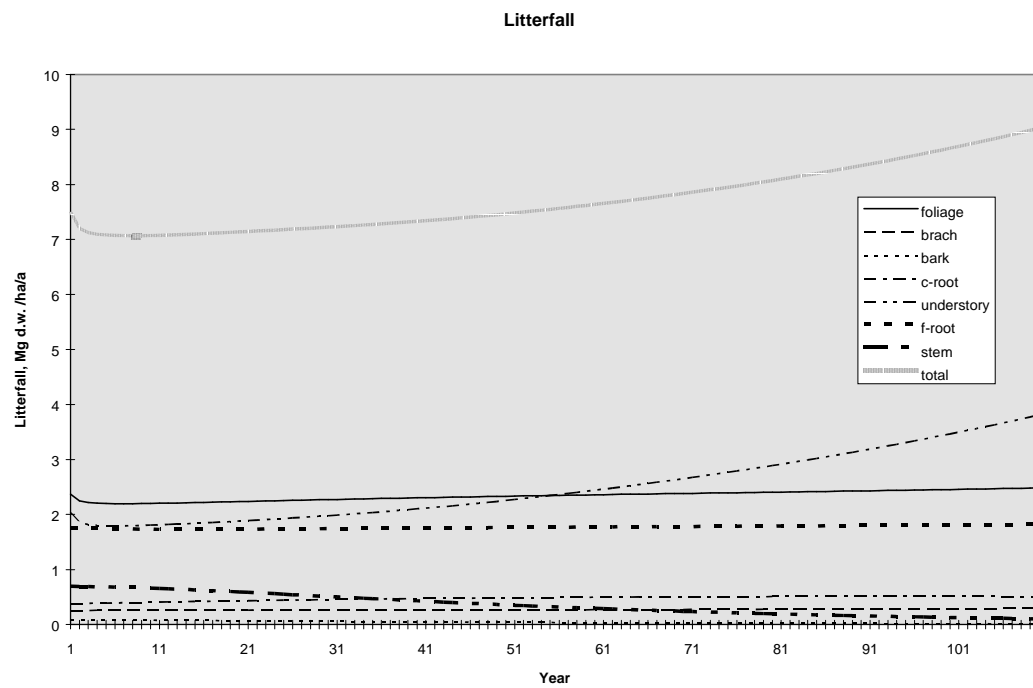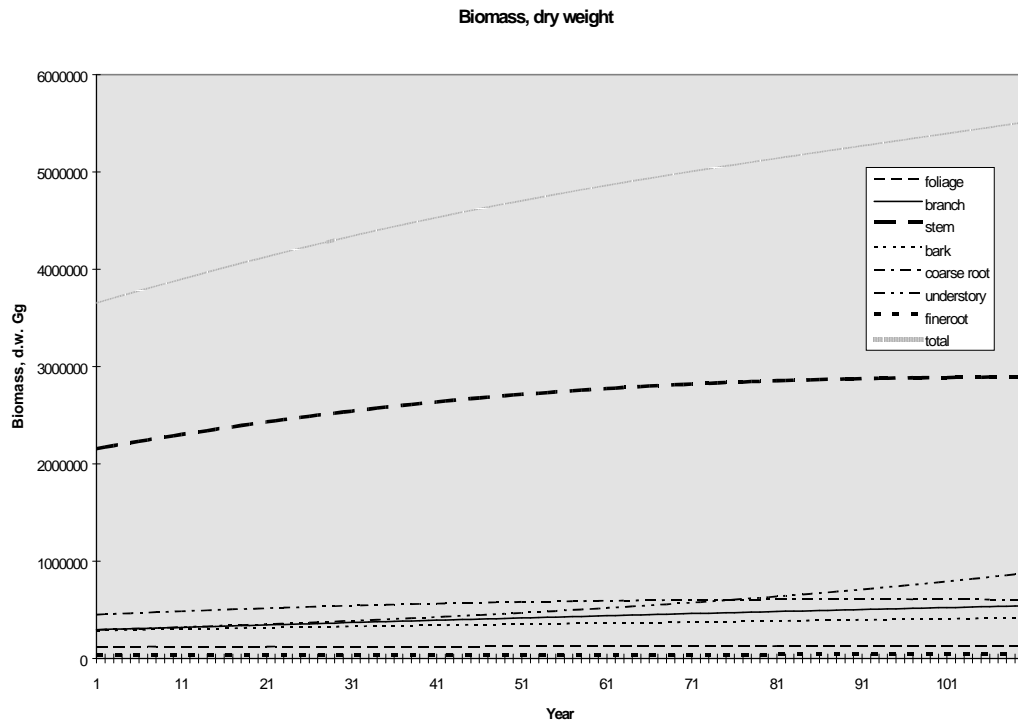
Biomass, dry weight

Litterfall

Figure 17. Development of biomass and litterfall in the Angara-Lena Southern Taiga ecoregion excluding stand replacing disturbances and harvesting.

5. Discussion and conclusions

The aim of this study was to develop a method to assess the carbon budget for tree biomass at ecoregional level in Siberia. The calculation method was developed based on the structure of the existing database and models describing tree growth and biomass allocation available at IIASA. Stand level analyses show that the described method simulates vegetation carbon budget in a plausible manner. This forms the basis for the application of the method for regional assessments. The tree biomass carbon budget presented here and that of the soil organic matter presented by Liski (1997) form the total forest carbon budget.

There are, however, several considerations that should be taken into account at the regional assessments. First, the existing growth equations are for evenaged stands. In Siberia and the Far East, 40-50% of the coniferous stands are unevenaged (the growing stock consists of trees of more than two, and usually of all age groups) or gradually unevenaged (the growing stock consists of trees of more than one canopy layer in which dominant species belong to different age groups of different types of age structure) (Shvidenko *et al.* 1996b). In the existing approach, the effect of stand structure could be included by decreasing density classes. Site index could be changed too, but in reality site index should be the same regardless of stand structure. Consideration of evenaged/unevenaged structure in the calculations is, however, difficult, since there are difficulties for the moment to get required information for the level of SVOs. Moreover, there are not yet growth equations for unevenaged stands to be applied for total Siberia. Neglecting the unevenaged structure leads to an overestimation of the growth and the carbon sequestration.

Second, there is also a concern related to the stand structure, and specifically to mixed species stands. The proportion of mixed species stands can be significant. However, mixed species stands are indirectly considered in existing calculations, since SVOs have been formed based on species groups (coniferous, soft deciduous species, and hard deciduous species). Detailed consideration of mixed species stands is difficult, since there are difficulties to get required information for the level of SVOs.

Third, stand replacing disturbances are currently included in a very simple way. Forest fires could be considered in more detail by taking into account climatic conditions when determining occurrence of fire. Also insect outbreaks and diseases could be considered as a part of disturbances.

Fourth, nearly 65% of the Siberian forests grow in areas with permafrost (Shvidenko and Nilsson 1996). Consideration of permafrost in the forest carbon budget is important, since evidently it affects both the forest growth and the soil organic matter decomposition. The forest growth equations used, however, take into account the effect of permafrost since they are based on measured data, and also through the site index.

Fifth, the availability of input data for total Siberia limits the use of more detailed approaches, i.e. the use of gap-type models which would take into account unevenaged structure, stand replacing disturbances and also changes in environmental conditions. Nevertheless, in ecoregions, where more detailed input data is available,

these methods should be applied in order to compare simple and more detailed approaches.

<u>Finally</u>, since part of the biomass is removed from the forests, the future fate of timber and wood-based products should also be considered. Methods similar to those used in Canada (Kurz *et al.* 1992) and Finland (Karjalainen *et al.* 1994) could be applied for the latter calculations.

Although there are many gaps in the proposed methodology, it could serve as a first step towards a dynamic approach for assessment of the future carbon budget of the Siberian forests.

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Calculation of carbon balance for Siberian forest soils

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Abstract

Different models describing the dynamics of organic C in forest soils were developed and then compared. The model judged to describe the dynamics of soil C in the most realistic way contains five compartments for different litter and three for soil organic matter (the so called Soil C model).

Temperature was considered to be the most important climatic factor that regulates the decomposition in boreal forests. The effective temperature sum with a +5°C threshold was chosen to describe the temperature impact on the decomposition. The application of the developed models was tested on the issues of impacts of species, harvesting intervals and harvesting residues left on the site.

For a full-scale application of the developed soil carbon models for Siberia and Russia, the special features of permafrost soils and peatlands need to be added to the models.

1. Introduction

Soils of Russia have been estimated to contain about 340 Pg organic carbon C (Rozhkov *et al.* 1996), and the soils of the former Soviet Union 404 Pg (Vinson & Kolchugina 1993). This is roughly half of the present amount of C in the whole atmosphere (Watson 1990), and 7-12 times more than the C storage of vegetation in Russia (a review of the estimates can be found in Karjalainen 1997). Owing to the major proportion of the C storage of terrestrial ecosystems and the large absolute C amount, changes in the soil C storage may significantly affect the C balance of terrestrial ecosystems in Russia and, consequently, the CO_2 concentration of the atmosphere.

The soil C balance of boreal taiga forests is important to the whole Russian soil C balance, as 64% of the soil C storage in Russia is found in the soil of these forests (Rozhkov *et al.* 1996). Factors which may potentially induce changes in this balance are natural disturbances, such as forest fires and damage caused by insects and fungi, human management of the forests and climate change. During a wild fire in boreal forests, 25-75% of the C in the organic layer may be lost, but the instant loss of organic C from mineral soil is negligible (Dyrness *et al.* 1989). Nevertheless, the long-term effects of successive wild fires on the soil C storage are not known. In

northern hardwood stands, clear cutting may cause about 50% decline in the C storage of the organic layer, but the storage returns to the preharvest level after few decades (Aber *et al*. 1978, Covington 1981, Federer 1984). The organic matter content in the mineral soil is probably quite resistant to changes (Cooper 1983). For boreal forests, quantitative estimates on the effects of forest harvests are scarce. Climate warming enhances decomposition of organic matter (Mikola 1960, Berg *et al*. 1993), but also the growth of boreal forests (Koivisto 1970, Pastor & Post 1988), and the changes in the soil C balance depend on how these processes are changed in relation to each other. The results of the effects of climate warming on the soil C storage of boreal forests remain controversial, since model simulations suggest both a decrease (Kirschbaum 1993) and an increase (Pastor & Post 1988, Townsend 1992). In Finland the equilibrium soil C storage has been measured to increase with increasing temperature (Liski & Westman 1996).

Aside the changes in the C storage of upland forest soils, changes in the C storage of permafrost soils and peatlands are of major importance to the Russian soil C balance. Special features of these latter soils can not be ignored when studying the soil C balance at the level of whole Russia, because the disturbances affect the C balance of these soils differently than the balance of upland forest soils, and permafrost and peatland soils contain a considerable proportion of the total soil C storage in Russia. One third of the total soil C in Russia is stored in litter and peat layers, and half of the soil C in taiga forests is found in permafrost soils (Rozhkov *et al*. 1996). In the Angara-Lena ecoregion, which was chosen as the test area for this study, a negligible proportion of the soils are, however, permafrost soils or peatlands. For this reason, this study deals with the C balance of upland forest soils, and the special features of permafrost soils and peatlands need to be added to this approach when applying it for other areas.

The aim of this study was to develop a method for calculating the C balance of Russian forest soils in Siberia. The calculation method was developed in close cooperation with the development of the approach for calculating the C balance of vegetation in Siberia (Karjalainen 1997). The reason is that these two calculations are linked such that the output of the vegetation calculations is used as input for the soil C calculations in order to estimate the total C balance of the entire forest ecosystems. In this paper, first, the structure of three different models is described. Second, the models are calibrated and tested for the conditions of southern Finland due to limited information on Russian forests for this purpose. Third, the models are calibrated for the conditions in Angara-Lena ecoregion. Fourth, the usefulness of the models for a wider application by the IIASA Forest Study is tested. Fifth, the model concept considered most appropriate is applied for investigation of the effects of tree species and forest harvesting on the soil C storage at stand level in the Angara-Lena ecoregion in Siberia.

2. Structures of the investigated models

2.1. General structure

Different disturbances in forests, for instance forest fires and harvests, leave a varying amount of different litter components at the site and affect the C balance of the soil differently. This is because chemically and physically different litter decomposes at different rates. In order to be able to investigate the effects of different disturbances on the soil C balance, litter entering the soil was divided into five compartments in the models (Fig. 1). These are foliage, branch, stem, coarse root and fine root litter compartments. This division needed to be made on the basis of the litter origin instead of the actual litter quality and at this level of detail, because the actual quality can not be followed in more detail in the database available at the IIASA Forest Study. Also, for this reason, changes in the litter quality during decomposition could not be utilized when modeling the decomposition.

Fresh litter decomposes rapidly, but gradually the decomposition rate decreases with the age of the litter (e.g. Berg *et al*. 1982). The initially rapid decomposition is due to the decomposition of the most easily decomposable compounds. The decomposition rate decreases as more recalcitrant residues remain and new recalcitrant compounds are formed in the decomposition process. This kind of decomposition was described in the models by transferring organic matter from the litter compartments with high decomposition rates to soil organic matter compartments with lower decomposition rates. Neither the way of modeling this transfer nor the decomposition of soil organic matter are well known. It was decided to develop three different models and evaluate these models in light of the present knowledge on soil organic matter dynamics and the usefulness of the models for the IIASA Forest Study. In the three models, called CBM1, CBM2 and SoilC, the litter compartments are the same, but the transfer of organic matter from the litter compartments to the soil organic matter compartments and the dynamics of soil organic matter are described in a different way (Fig. 1).
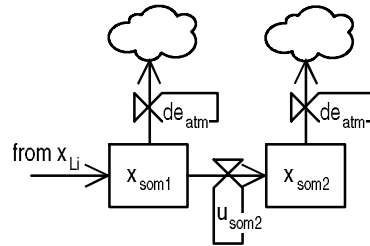
Litter compartments
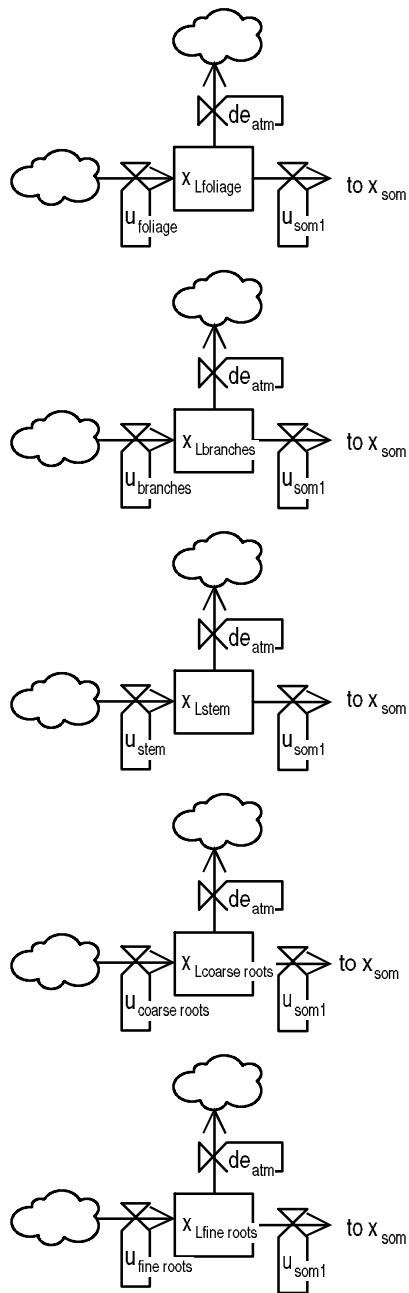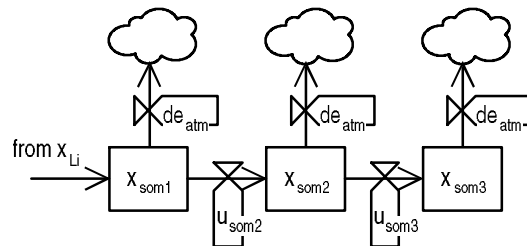
Soil organic matter compartments
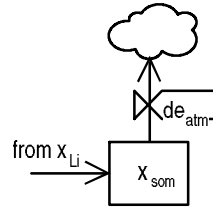
Figure 1. Outline of CBM1, CBM2 and Soil C models. The litter compartments are the same for all three models, but the soil organic matter compartments are different.

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2.2. Structure of CBM1

CBM1 is essentially similar to the soils module of the Canadian Forest Sector Carbon Budget Model, CFS-CBM (Kurz *et al*. 1992). In this model, litter enters the litter compartments, and a certain proportion of the C decomposed in these litter compartments is always transferred to the soil organic matter compartment. As a result of decomposition in the soil organic matter compartment, C is released only to the atmosphere (Fig. 1).

Denote the mass of C in litter compartment *i* at time *t* by $x_{Li}(t)$, the flow of C to that compartment by $u_i(t)$, and the decomposition rate in this compartment by k_{Li}. The dynamics of the mass of C in litter compartment *i* can be described as

$$\frac{dx_{Li}}{dt} = u_i(t) - k_{Li} x_{Li}(t), \tag{1}$$

i=foliage, branch, stem, coarse root and fine root litter.

Denote the mass of C in the soil organic matter compartment at time *t* by $x_S(t)$, the proportion of the decomposition in each litter compartment transferred to the soil organic matter compartment by *p*, and the decomposition rate in the soil organic matter compartment by k_S. The dynamics of the mass of C in the soil organic matter compartment can be described as

$$\frac{dx_S}{dt} = \sum_i p k_{Li} x_{Li}(t) - k_S x_S(t). \tag{2}$$

2.3. Structure of CBM2

The compartments of CBM2 are the same as the compartments of CBM1, except that CBM2 has two soil organic matter compartments instead of one (Fig. 1). The second soil organic matter compartment has been added to allow a more flexible description of the dynamics of the soil organic matter. The transfer of organic matter between these two soil organic matter compartments is defined in the same way as the transfer from the litter compartments to the first soil organic matter compartment, i.e. a certain proportion of the decomposed C in the first soil organic matter compartment is always transferred to the second. Due to lack of data, this proportion is assumed to be the same as for the transfer from the litter compartments to the first soil organic matter compartment. Carbon from the second compartment is only released to the atmosphere (Fig. 1).

The dynamics of the mass of C in litter compartments are described in the same way as in CBM1 (equation 1). For describing the dynamics of the mass of C in the soil organic matter compartments, denote the mass of C in litter compartment i at time t by $x_{Li}(t)$, the masses of C in the first and second soil organic matter compartments at time t respectively by $x_{S1}(t)$ and $x_{S2}(t)$, the proportion of the decomposition in each litter compartment or in the first soil organic matter compartment transferred to the subsequent soil organic matter compartment by p, and the decomposition rates in the first and second soil organic matter compartments respectively by k_{S1} and k_{S2}. The dynamics of the mass of C in the first soil organic matter compartment can be described as

$$\frac{dx_{S1}}{dt} = p \sum_i k_{Li} x_{Li}(t) - k_{S1} x_{S1}(t), \qquad (3a)$$

i=foliage, branch, stem, coarse root and fine root litter.

The dynamics of the mass of C in the second soil organic matter compartment as

$$\frac{dx_{S2}}{dt} = p k_{S1} x_{S1}(t) - k_{S2} x_{S2}(t) \qquad (3b)$$

2.4. Structure of SoilC

SoilC has the same litter compartments as CBM1 and CBM2, but three compartments for soil organic matter (Fig. 1). Also, the transfers from the litter compartments to the first soil organic matter compartment and between the soil organic matter compartments are defined in a different way than in the two CBMs. This is done to avoid the use of the rather arbitrary transfer proportion and including a delay in the formation of soil organic matter from fresh litter.

The transfer of organic matter from the litter compartments to the first soil organic matter compartment is based on findings by Melillo *et al.* (1989) and Aber *et al.* (1990). They suggest that the decomposition of litter entering soil can be divided into two phases: into an initial phase of rapid mass loss and a consecutive phase of much slower mass losses. During the whole initial phase the decomposition rate remains the same, and this rate is quite accurately described by the decomposition rate during the first few years of decomposition. The initial phase ceases when about 20% of the original mass remains. This percentage seems to be quite similar for different litter, but the original litter quality determines the actual decomposition rate during the initial phase and, consequently, the time needed to reach this loss of masses. Litter of originally different quality is transformed to a quite common chemistry during the initial period, and, therefore, originally different litter tends to decompose at a rather similar rate after the initial phase. After the initial phase, the loss of masses is considerably slower, and the initial decomposition rate would greatly overestimate the losses.

Based on this kind of description of the decomposition of litter, in the Soil C model, litter enters the litter compartments and resides in the same until 20% of the initial mass remains. This residue is then transferred to the first soil organic matter compartment. Even if Aber *et al.* (1990) determined this residue proportion only for small-sized foliage and fine root litter, the same proportion is used for all litter compartments. The calculations of the total soil C storage are not especially sensitive to this assumption, because the decomposition rates of the branch, stem and coarse root litter are rather close to the decomposition rate of the first soil organic matter compartment.

The method of transfer between the soil organic matter compartments is adopted from a simple model used for investigating the soil organic matter dynamics in southern Finland (Liski *et al.* 1996). In this MaaC model, soil organic matter is divided into five consecutive compartments according to the age of the organic matter. These compartments divide soil organic matter into age classes of 0-5 years, 6-20 years, 21-100 years, 101-1000 years and over 1000 years. Fresh litter enters the first compartment and the residue of the input that has not decomposed in the compartment during its stay there is transferred to the successive compartment. In the fifth compartment organic matter stays until is has decomposed. The SoilC model used in this IIASA study can be considered as a modification of this MaaC model, in which the two youngest compartments are replaced by the litter compartments as described above.

Denote the mass of C in litter compartment i at time t by $x_{Li}(t)$, the flow of C to that compartment by $u_i(t)$, the decomposition rate in this compartment by k_{Li}, the residue proportion transferred to the soil organic matter compartment by p, and the residence time of litter in this compartment by t_{Li}. The dynamics of the mass of C in the litter compartments can be described as

$$\frac{dx_{Li}}{dt} = u_i(t) - k_{Li}x_{Li}(t) - pu_i(t - t_{Li}). \qquad (4)$$

i=foliage, branch, stem, coarse root and fine root litter.

The residence time of litter in litter compartment i, t_{Li}, can be calculated on the basis of p and k_{Li} as

$$t_{Li} = \frac{\ln p}{-k_{Li}} \qquad (5)$$

For describing the dynamics of the mass of C in the soil organic matter compartments, denote the mass of C in soil organic matter compartment i at time t by $x_{Si}(t)$ and the flow of C to that compartment by $u_{Si}(t)$. Since the soil organic matter compartments are linked, and that the outflow of non-decomposed C from compartment i is the inflow to compartment $i+1$, the dynamics of the weight of organic C in compartment i

can be described as

$$\frac{dx_{Si}}{dt} = u_{Si}(t) - k_{Si}x_{Si}(t) - u_{Si+1}(t),$$ (6)

$i=1$, 2 and 3.

The input to the first soil organic matter compartment at time t equals the outflow of non-decomposed material from the litter compartments at that time

$$u_{S1}(t) = p\sum_i u_i(t - t_{Li}).$$ (7)

The transfer from a preceding soil organic matter compartment to the next one at time t, $u_{Si+1}(t)$, equals the residue of the input that has not decomposed in the preceeding compartment during the time, t_{Si}. Assuming k_{Si} is constant, this can be calculated as

$$u_{Si+1}(t) = u_{Si}(t - t_{Si})e^{-k_{Si}t_{Si}},$$ (8a)

and, in case k_{Si} varies with time, as

$$u_{Si+1}(t) = u_{Si}(t - t_{Si})e^{-\int_{t-t_i}^{t} k_{Si}(t)dt}.$$ (8b)

3. Parameterization of the models for the conditions of southern Finland

The decomposition rates of litter are reasonably well known, because they can be directly measured. On the other hand, the rates of decomposition of soil organic matter and the transfer proportions of the CMB1 and CBM2 can not be directly measured, and the knowledge on these parameters is much more inaccurate. One approach to approximate these parameters is to adjust them in the models to obtain equilibrium soil C storages equal to the measured ones. The litter input to the soil as well as the soil age needed for reaching the equilibrium storage also need to be known for this approach. The soil age is used as a measure of the dynamics of the storage for obtaining correct dynamics for the storage in addition to the correct equilibrium quantity. These kinds of measurements were not available for forests in Russia, but they were available for forests in southern Finland. Therefore, it was decided to first calibrate the models for the conditions of southern Finland and then modify the decomposition rates for the conditions in Russia.

In southern Finland the soil C storage reaches equilibrium with soil ages in 1500-2000 years (Liski *et al*. 1996). This result has been obtained using a simple dynamic model, MaaC, which was calibrated with the help of measurements of the C storages in 26 forest soils ranging from 200 to 5300 years of age on the west coast of southern Finland. At sites, where the average rate of C input to the soil is 0.41 kg m^{-2} yr^{-1} (Table 1), the equilibrium soil C storage is about 10 kg m^{-2} (Liski & Westman 1995).

For calibrating CBM1 and CBM2 for the conditions of southern Finland, the decomposition rates of the soil organic matter compartments and the transfer proportions were adjusted to satisfy these constraints, i.e. to give the equilibrium soil C storage equal to about 10 kg m^{-2} at the soil age of about 1500 years with a total C input rate of C to the soil equal to 0.41 kg m^{-2} yr^{-1}. For the soil organic matter compartments of the SoilC model, parameters of earlier MaaC model were used in order to maintain the measurements of the equilibrium soil C storages as independent test data for this model. The decomposition rates of the litter compartments were taken from literature and the same rates were used in all three models (Table 2). In these calculations, the total input of C to the soil was divided into the litter compartments as shown in Table 1; the above-ground production of ground vegetation was merged with the foliage compartment and the below-ground production was merged with the fine root compartment.

Table 1. Average input rate of C to the soil at high productivity (*Myrtillus* type) Scots pine stands in southern Finland.

Biomass compartment	kg m^{-2} yr^{-1}
Trees	
Foliage	0.0609 [1]
Branches	0.0306 [1]
Stem	0.0866 [1]
Coarse roots	0.0452 [1]
Fine roots	0.100 [2]
Ground vegetation	
Above ground	0.0421 [1]
Below ground	0.0280 [1]
Fine roots	0.0200 [2]
Sum	0.413

[1] the values of biomass production at a 45 year old stand (Mälkönen 1974) were multiplied by 0.5 for conversion to C and by 0.7 for obtaining average production values over the life span of the stand. Multiplier 0.7 assumes the same relation between the average stem wood production over 100 years and annual stem wood production at the stand age of 45 years for the production of all biomass compartments (Koivisto 1959).

[2] values for 120 year old Scots pine stand in central Sweden (Persson 1983)

Table 2. Parameter values of the models for coniferous forests in the conditions of southern Finland.

Model	Parameter name	Parameter value	Note
All models	$k_{Lfoliage}$	0.25 yr^{-1}	decomposition rate of Scots pine needles over the first 5 years of decomposition (Berg *et al*. 1982)
	$k_{Lbranches}$	0.08 yr^{-1}	decomposition rate of Douglas fir branches over the first 2 years of decomposition (Fogel & Cromack 1977)
	k_{Lstem}	0.034 yr^{-1}	decomposition rate of pine and spruce stems over the first 70 years of decomposition (Krankina & Harmon 1995)
	$k_{Lcoarse\ roots}$	0.08 yr^{-1}	assumed equal to branches
	$k_{Lfine\ roots}$	0.25 yr^{-1}	assumed equal to foliage
CBM1	p	0.026	adjusted for the calibration constraints (see text)
	k_S	0.002 yr^{-1}	adjusted for the calibration constraints (see text)
CBM2	p	0.115	adjusted for the calibration constraints (see text)
	k_{S1}	0.03 yr^{-1}	needs to be a little smaller than k_{Lstems}
	k_{S2}	0.0015 yr^{-1}	adjusted for the calibration constraints (see text)
SoilC	p	0.2	Aber *et al*. 1990
	k_{S1}	0.03 yr^{-1}	needs to be a little smaller than k_{Lstems}
	k_{S2}	0.002 yr^{-1}	from MaaC model (Liski *et al*. 1996)
	k_{S3}	0.001 yr^{-1}	from MaaC model (Liski *et al*. 1996)
	t_{S1}	80 yr	from MaaC model (Liski *et al*. 1996)
	t_{S2}	900 yr	from MaaC model (Liski *et al*. 1996)

With the parameter values obtained using this calibration procedure and the constant input rate of C to the soil (Table 2), all three models predicted the accumulation of soil C with the age of the soil in the similar way as the MaaC model (Fig. 2), which has been found to predict these dynamics of soil C correctly in southern Finland.
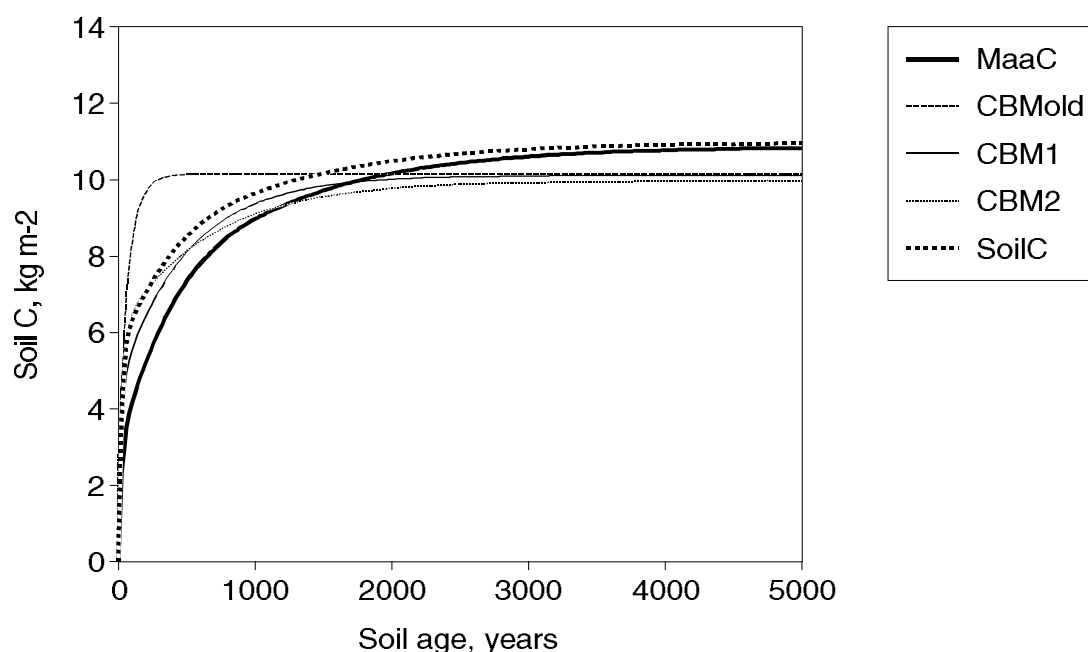

Figure 2. Accumulation of C in the soil at a *Myrtillus* type site with soil age in southern Finland as predicted by different models. CBMold represents CBM1 parameterized by using the transfer proportion of 17%.

In the earlier versions of the CBM soils module, 17% of decomposed C in the litter compartments have been transferred to the soil organic matter compartment (Kurz *et al*. 1992). Using this transfer proportion, the decomposition rate of the soil organic matter compartment needs to be 0.0134 yr^{-1} to get the equilibrium soil C storage equal to 10 kg m^{-2}. With this decomposition rate, however, the soil C storage reached equilibrium too early, in about 200 years, indicating unrealistically fast dynamics of the soil organic matter (Fig. 2). The transfer proportion found appropriate here, 2.6% (Table 2), is considerably smaller than in other models with similar structure. In other models this proportion has ranged from 6% to 50% (Jenkinson & Rayner 1977, Aber *et al*. 1978, Dewar 1991, Berg *et al* 1995, Kokorin & Nazarov 1995).

4. Testing of the models for the conditions of southern Finland

For testing the SoilC model for the conditions of southern Finland, equilibrium soil C storages were calculated for four different forest types using the model, and the values were compared with measured storages in these forest types which represent different site productivities. Because the measured storages were for sites dominated by coniferous vegetation producing fairly homogenous coniferous litter, the productivity was assumed to affect only the input rate of C to the soil, while the decomposition rates were kept similar independent of the forest type. This kind of testing could be done for the SoilC model alone, because the measurements of the equilibrium storages were used for defining the parameter values of CBM1 and CBM2 (see Table 2).

Because the actual input rates of C to the soil were not available for other forest types than *Myrtillus* type, the input rates of the other forest types were assumed to be proportional to the input rate of *Myrtillus* type in the same way as stemwood production. Consequently, the input rates of the *Myrtillus* type (Table 1) were multiplied by 0.5 for the least productive *Calluna* type, by 0.86 for the next fertile *Vaccinium* type and by 1.07 for the most productive *Oxalis-Myrtillus* type (Ilvessalo & Ilvessalo 1975).

The soilC model seemed to predict a larger equilibrium soil C storage than what has been measured in the organic and 1 m deep mineral soil layers (Fig. 3a). This difference was mainly due to the difference in the organic layer (Fig. 3b), whereas the amount of C in mineral soil was quite correctly calculated (Fig. 3c). One reason for the difference in the estimate of the organic layer is that the measurements have not covered the litter layer of the organic layer, but is included in the model calculations. On the other hand, the measurements of the organic layer may have included some C which is included in the soil organic matter compartments of the model. However, considering the differences in the definitions of the compared pools and the unspecific method of calculating the input rate of C to the soil in the forest types, SoilC model seems to be able to predict the equilibrium soil C storages reasonably well in southern Finland. CBM1 and CBM2 would have performed quite similarly in this test, because the calculated equilibrium storage is directly proportional to the input rate of C to the soil and the measured storages are proportional to each other in a rather similar way as the rate of stemwood wood production.
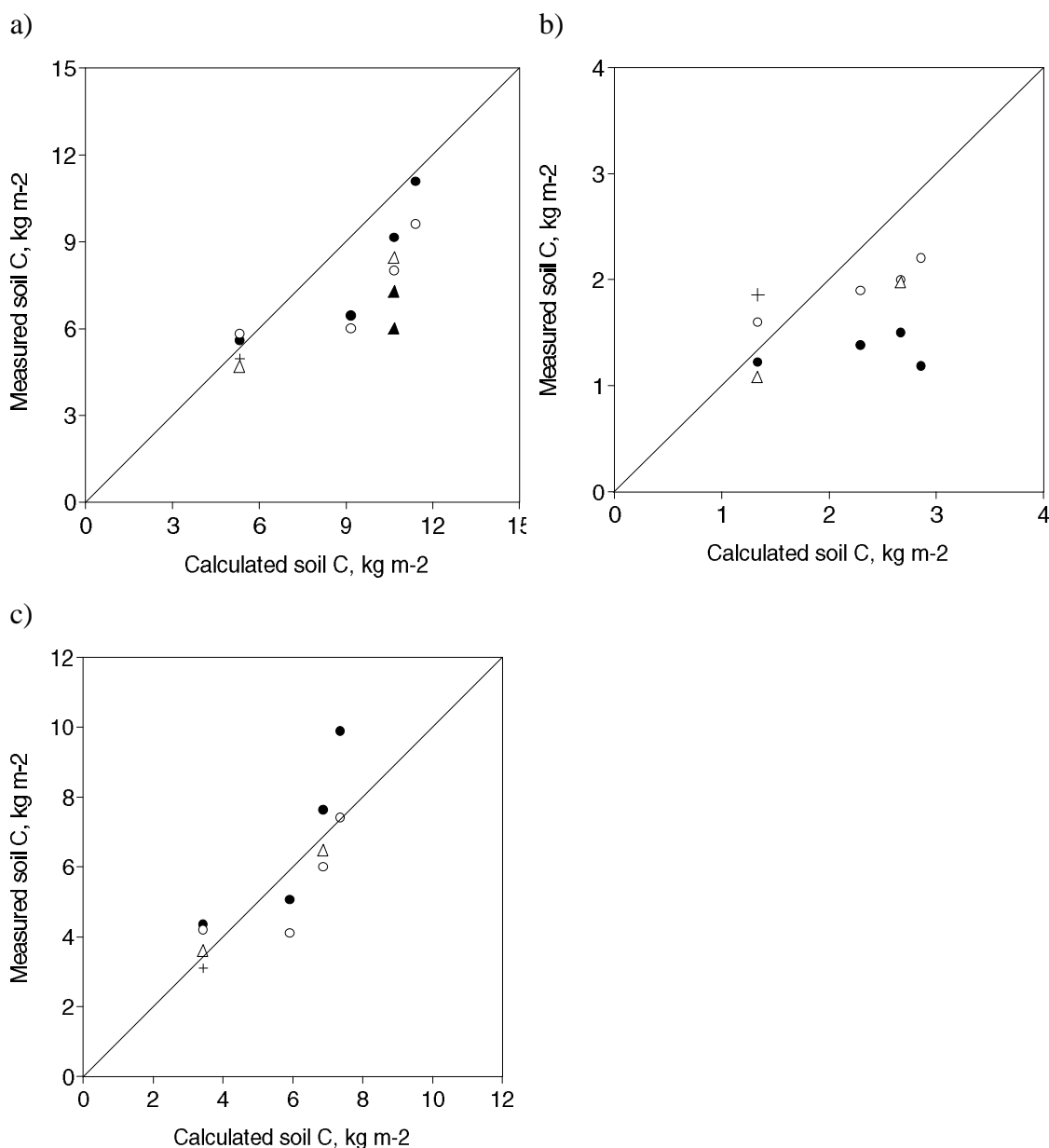
Fig. 3. Equilibrium soil C storages in southern Finland, as calculated by using the SoilC model, plotted against measured storages: a) the total calculated storage plotted against the measured storage in the organic layer plus the 0-1 m mineral soil layer, b) the sum of the above ground litter compartments, i.e. foliage, branch and stem litter compartments, plotted against the measured storage in the organic layer and c) the sum of the soil organic matter compartments plotted against the measured storage in the 0-1 m mineral soil layer. The filled dots (n=47-641, Tamminen 1991), open dots (n=5-11, Liski & Westman 1995) and open triangles (n=4, Liski&Westman 1996) are averages for forest types; the crosses (Liski 1995) and filled triangles (Westman *et al.* 1994) are measurements from one site. The measurements of mineral soil by Tamminen (1991) were for the 0-30 cm layer and those by Liski (1995) for the 0-40 cm layer, and they were multiplied by 1.18-1.67 to represent the 0-1 m layer according to Liski & Westman (1995).

5. Effect of climate on the decomposition rates

Actual evapotranspiration, which sums up information on temperature and moisture, has often been found to be the best climatic factor to explain differences in the decomposition rates of litter over large areas covering climates of different vegetation zones (Meentemeyer 1978, Berg *et al*. 1993). However, in the cold conditions of the boreal and subarctic zones the lack of moisture is rarely regulating decomposition and temperature alone is considered as one of the most important climatic factors affecting the decomposition in well-drained soils (Mikola 1960, Moore 1984). For instance, on a transect ranging from northern Finland to northern France, the first year loss of masses in Scots pine needles is closely associated with the annual mean temperature (Mikola 1960, Berg *et al*. 1993) (Fig. 4).
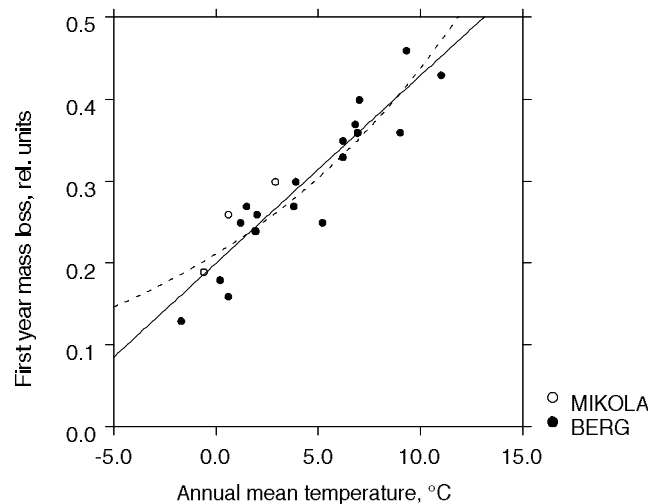
Figure 4. The first year loss of masses in of Scots pine needles, measured by litter bags, plotted against the annual mean temperature on a gradient from northern Finland to northern France (open dots from Mikola 1960 and filled dots from Berg *et al*. 1993). The solid line represents the linear regression (mass loss=0.0200+0.0229 temperature, R^2=0.86) and the dashed line the Q10 relationship (mass loss=0.2109 $e^{\ln(2.078) \text{ temperature } 0.1}$, R^2=0.83).

The dependence of decomposition on climate is known only for the early stages of decomposition, i.e. for the most easily decomposable compounds. When modeling the dynamics of soil organic matter it is common to assume this dependence for all soil organic matter, even if the most easily decomposable compounds represent only a minor proportion of the soil organic matter (Jenkinson & Rayner 1977, Liski *et al*. 1996). The results of the model calculations about the effects of climate warming on the soil C storage, for instance, are very sensitive to this assumption in the boreal zone in particular, because substrate availability may not as easily limit decomposition as in warmer conditions (Townsend 1992).

One way to test this assumption is to calculate equilibrium soil C storages for different temperatures using the models and compare these calculated storages to measured equilibrium storages in different temperatures. In order to be able to relate the variation in the measured soil C storages to temperature, the measurements need to be

made at such sites where factors affecting the soil C balance other than temperature are similar.

Such measurements are available for two forest types from a temperature gradient in Finland. The C storage of the organic layer was not found to be associated with temperature, but the C storage of 0-1 m mineral soil layer increased with increased temperature (Liski & Westman 1996) (Fig. 5). The p-value for this increase of the C storage with the annual mean temperature was 0.0008 when including both forest types simultaneously for the test (n=30), and 0.012 among the less productive *Calluna* type sites (n=15) and 0.017 among the more productive *Myrtillus* type sites (n=15) when testing separately inside the forest types.

For calculation of the equilibrium soil C storages for different temperatures by using the models, the input rate of C to the soil was estimated for the annual mean temperatures ranging from -2 to 4°C. The effect of temperature on the input rate of C to the different litter compartments of the models was assumed to be similar as the effect of temperature on the growth rate of stemwood (Koivisto 1970), because direct estimates of the input were not available. The input rates of *Myrtillus* type sites with a +4°C annual mean temperature were used as reference input rates (Table 1), and they were multiplied by 0.5 to obtain the reference rates for *Calluna* type sites (Ilvessalo & Ilvessalo 1975). These reference rates were multiplied by 0.95, 0.87, 0.72, 0.52 and 0.27 to get the input rates for temperatures 2.8, 1.6, 0.4, -0.8 and -2 °C, respectively.

The dependence of the decomposition rate on the annual mean temperature was calculated by fitting a linear regression to the data collected by Mikola (1960) and Berg *et al.* (1993) (Fig. 4). The linear regression was used instead of a Q10 relationship, because the association between the decomposition rate and the annual mean temperature seemed to be linear. The Q10 relationship would have overestimated the decomposition rate especially for temperatures less than 1°C. According to the linear regression, the decomposition rate increases by a factor of 0.0787 for every one degree increase in the annual mean temperature.

This temperature dependence of decomposition was first assumed for all litter and soil organic matter compartments of the models. Choosing the annual mean temperature equal to +4°C as the reference temperature, T_0, and denoting the decomposition rate of litter compartment i in this temperature by $k_{Li+4°C}$, the decomposition rate of soil organic matter compartment i by $k_{Si+4°C}$ and temperature sensitivity of 0.0787 by s_L, the decomposition rates of the litter and soil organic matter compartments of the models were calculated for the annual mean temperatures ranging from -2 to 4°C as
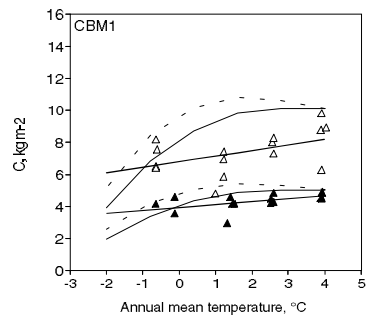
$$k_{Li}(T) = k_{Li+4C}(1 + s_L(T - T_0)),\qquad(9)$$

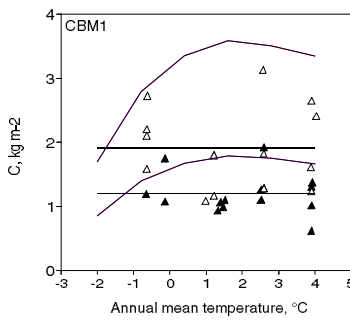i=foliage, branch, stem, coarse root and fine root litter, and

$$k_{Si}(T) = k_{Si+4C}(1 + s_L(T - T_0)),\qquad(10)$$
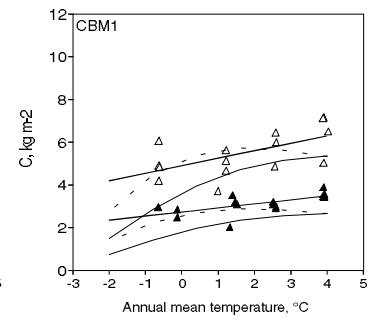
i=1 for CBM1, i=1,2 for CBM2 and i=1,2,3 for SoilC.

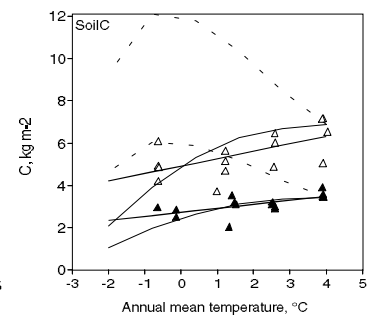**Figure 5.** The equilibrium C storage of the organic layer, the 0-1 m mineral soil layer and the sum of these layers plotted against the annual mean temperature in Finland. The filled triangles represent measurements at low productivity *Calluna* type Scots pine sites and the open triangles the measurements at higher productivity *Myrtillus* type Norway spruce sites. The thick solid lines represent statistical models fitted to the data for the C storage in the organic plus the 0-1 m mineral soil layers. This line is calculated by summing up the values from the separate statistical models for the organic layer and mineral soil. The thin lines represent equilibrium storages calculated by using CBM1, CBM2 and SoilC models; the dashed lines assume the same temperature dependence for soil organic matter decomposition as for litter. The solid lines assume that the decomposition of soil organic matter is less sensitive to temperature than the decomposition of litter.

CBM1 and CBM2 models predicted the largest total soil C storage at +2°C temperature and the SoilC model at 0°C temperature (Fig. 5). These model predictions do not agree with the trend in the measurements, which indicates a decreasing soil C storage with decreasing annual mean temperature from 4°C to -1°C. Assuming that the input rates of C to the soil have been estimated correctly for the different temperatures, the overestimation of the C storages in the temperatures below 4°C is caused by underestimating the decomposition rates in these low temperatures. The temperature dependence of decomposition is most accurately known for the most easily decomposable compounds (Fig. 4) found in the litter compartments of the models. It is most probable that the temperature dependence of the decomposition of the soil organic matter compartments has been overestimated by assuming the same dependence for soil organic matter as for litter. The results of SoilC model give support for this idea. In low temperatures the model greatly overestimated the C storage of mineral soil (Fig. 5i), which contains the oldest soil organic matter in these soils (e.g. Tamm & Holmen 1967). On the other hand, the model predicted the C storage of the organic layer containing younger soil organic matter reasonably well for the different temperatures (Fig. 5h). Paying more detailed attention to the absolute differences between the measurements and the model predictions aside this kind of consideration of the trend was not thought to be appropriate. The measurements and the model calculated storages are for slightly different parts of the soil C storage, as noted before, and the actual absolute input rate of C to the soil was not known accurately enough for such comparisons.

To overcome this discrepancy between the model predictions and the measurements, the decomposition rate of the soil organic matter compartments of the models was chosen to be less sensitive to temperature as the decomposition rate of the litter compartments. The temperature dependence of the decomposition of the first soil organic matter compartment, s_{S1}, was assumed to be a certain proportion, v, of the temperature sensitivity of the litter compartments, s_L:

$$s_{S1} = v s_L \,. \tag{11}$$

For simplicity, the temperature sensitivity of the successive soil organic matter compartments, s_{Si}, in the CBM2 and SoilC models was assumed to be of the same proportion, v, of the sensitivity of the preceeding compartment, s_{Si-1}:

$$s_{Si} = v s_{Si-1} \,. \tag{12}$$

The parameter v was chosen to be highest, which resulted in a decreasing trend in the equilibrium soil C storage with decreasing temperature from 4°C.

For CBM1 this value was 0.07, for CBM2 0.16 and for the SoilC model 0.13. These values indicate that the decomposition rate of soil organic matter is considerably less sensitive to temperature than that of litter. The equilibrium soil C storages calculated using these temperature sensitivities for the soil organic matter compartments of the models are shown in Fig. 5.

The decomposition rates reported in Table 2 can be adjusted for different annual mean

temperatures for the conditions in western Europe using equations 9, 10, 11 and 12. This dependence of the decomposition rates on the annual mean temperature is, however, unlikely valid for most of Russia due to the difference in the continentality of the climates. Extremely cold winters of a continental climate result in low annual mean temperatures, even if hot summers provide a lot of energy for decomposition. The effective temperature sum is probably a better variable in explaining the effect of temperature on the decomposition rate, because it summarizes the length of the decomposition period and the amount of energy for decomposition during that active period.

For modifying equations 9 and 10 to describe the effect of the effective temperature sum on the decomposition rate, the annual mean temperature and the effective temperature sum with +5°C threshold were calculated for the sites of the decomposition study by Berg *et al*. 1993 (Fig. 4). The climate data needed for the calculation were obtained on the spatial resolution of 0.5 degrees from the Cramer and Leemans climate data base, which is an improved version of that described by Leemans and Cramer (1991).

The calculated annual mean temperatures were very similar to the ones reported by Berg *et al*. (1993), the linear correlation coefficient between the calculated and reported values was 0.986. Therefore, the climate data was thought to be appropriate for calculating the temperature sums for the sites as well. To express the relation between the temperature sum and the annual mean temperature, a linear regression was fitted to the data on reported annual mean temperature and the calculated temperature sum. According to this regression, one degree day change in the effective temperature sum means a 0.00785 °C change in the annual mean temperature; the R^2 value for this regression was 0.94. Choosing the effective temperature sum for the conditions of southern Finland equal to 1300 degree days as the reference temperature sum, ETS_0, and denoting the respective decomposition rate by k_{1300}, the dependence of the decomposition rate of litter compartments on the temperature sum can be expressed as

$$k_{Li}(ETS) = k_{1300}(1 + 0.00785s_L(ETS - ETS_0)),$$ (13)

and the decomposition rates of the soil organic matter compartments as

$$k_{Si}(ETS) = k_{1300}(1 + 0.00785s_{Si}(ETS - ETS_0)).$$ (14)

The decomposition rates of the litter and soil organic matter compartments of the models reported in Table 2 can be adjusted for climates with different temperature sums using these equations and equations 11 and 12. The temperature sums calculated for the decomposition measurements ranged from 470 to 2210 degree days, and, consequently, the equations are considered valid at least for this range of temperature sums.

6. Effect of tree species on the decomposition rates

Litter of different plant species decomposes at a different rate due to the differences in the quality of the litter (e.g. Eijsackers & Zehnder 1990). The decomposition rate generally increases in the order of conifers, hard deciduous trees and soft deciduous species. Since the proportion of hard deciduous species is negligible in Angara-Lena ecoregion (Karjalainen 1997), the decomposition rates were estimated only for the litter of conifers and soft deciduous species in this study. The decomposition rates of the soil organic matter compartments were assumed independent of the litter quality, because litter of originally different quality was thought to be transferred to a quite common chemistry when leaving the litter compartments of the models. This assumption follows from the description of decomposition by Melillo *et al*. (1989) and Aber *et al*. (1990), as explained in "2.4 Structure of the SoilC".

The decomposition rates reported in Table 2 were used as the reference rates for the conditions of southern Finland with respect to litter for all coniferous species. The decomposition rates for litter of deciduous trees in southern Finland were approximated on the basis of information in the literature (Table 3).

Table 3. Decomposition rates for the litter compartments of the models for deciduous forests for the conditions of southern Finland.

Parameter name	Parameter value	Note
$k_{Lfoliage}$	0.42 yr^{-1}	decomposition rate of birch leaves over the first 3 years of decomposition (Mikola 1960)
$k_{Lbranches}$	0.11 yr^{-1}	rate of coniferous branches multiplied by 1.32, which is the ratio between the decomposition rates of deciduous and coniferous stems
k_{Lstem}	0.045 yr^{-1}	decomposition rate of birch stems over the first 70 years of decomposition (Krankina & Harmon 1995)
$k_{Lcoarse\ roots}$	0.11 yr^{-1}	assumed equal to branches
$k_{Lfine\ roots}$	0.42 yr^{-1}	assumed equal to foliage

The decomposition rates of deciduous litter were assumed to be dependent on the effective sum in the same way as the decomposition of coniferous litter, and, consequently, equation 13 was used for adjusting the decomposition rates for different climate conditions. The validity of this assumption was tested by adjusting the decomposition rate of deciduous foliage litter for the conditions of northern Finland, and comparing the mass losses calculated by using this decomposition rate with the mass losses of birch leaves measured by Mikola (1960). During the first two years of decomposition, the calculated mass losses matched well with the measured mass losses; the difference was 4.6% after the first year and 1.6% after the second year. After the third year the matching was not that good; the calculated mass losses were 20% larger than the measured mass losses. Despite the mismatch after three years, which may also be caused by an error in the measurements, the use of the same temperature dependence for deciduous and coniferous litter was thought to be appropriate.

7. Evaluation of the models

7.1. Simulation of forest harvesting

For comparing the dynamics of soil C storage predicted by the CBM1, CBM2 and SoilC models, two subsequent forest harvests were simulated for a pine site (site index III, density 0.6) in the Angara-Lena ecoregion using the three models. Before the first harvest the soil C storage was run to equilibrium with the average annual input rate of C to the soil at a virgin site. This rate was approximated by dividing the total biomass production during a 180 year period, i.e. litter production during the period plus standing biomass at the end of the period, by the length of this period. The biomass production was calculated by using the equations of the standing biomass and mortmass as described by Karjalainen (1997). Of the total production of understory vegetation, 60% was assumed above ground and 40% below ground. One half of the production above ground was put to the foliage litter compartment of the models and the other half to the branch litter compartment. Similarly, one half of the production below ground was put to the fine root litter compartment and the other half to the coarse root compartment.

The average rate of C input to the soil totaled 0.397 kg m^{-2} yr^{-1}, of which 0.104 kg m^{-2} yr^{-1}, 0.0348 kg m^{-2} yr^{-1}, 0.102 kg m^{-2} yr^{-1}, 0.0466 kg m^{-2} yr^{-1} and 0.110 kg m^{-2} yr^{-1} was put to the foliage, branch, stem, coarse root and fine root litter compartments, respectively (Fig 6a). With this input rate of C to the soil, CBM1 predicted an equilibrium soil C storage equal to 9.08 kg m^{-2}, CBM2 equal to 8.94 kg m^{-2} and SoilC equal to 9.45 kg m^{-2} (Fig. 6b). The slightly different equilibrium storage of SoilC model in the simulation in Fig. 6b, some 10.1 kg m^{-2}, is due to rounding errors of the residence times of the litter compartments in the simulation, in which the time step was one year. According to CBMs, 3.2 kg m^{-2} of the equilibrium storage was in the above ground litter compartments and according to SoilC 2.5 kg m^{-2} (Fig, 7). The value of SoilC model is closer to the average of measurements of the C storage of the organic layer, 1.9 kg m^{-2} (range 0.7-2.6 kg m^{-2}, n=5), at comparable pine sites (site index III) in the southern taiga (Zabelina 1996). Undecomposed stems and large branches have not been included in the measurements of the organic layer, which is one reason for the smaller measured value.

Two clear cut harvests were simulated at an interval of 180 years. This rotation period, which is longer than the 100-120 years which is recommended for these kind of pine sites in the Angara-Lena ecoregion (Charles Backman pers. comm.), was chosen in order to follow the development of the soil C storage in overmature sites, too. This was considered reasonable, because such overmature sites are common in the Angara-Lena region (Karjalainen 1997). At the time of the forest harvests, all standing biomass except 20% of the stemwood was put to the respective litter compartments of the models. Understory vegetation was divided between the litter compartments as described above. Consequently, during the year of the harvests the C input to the foliage litter compartment was 0.568 kg m^{-2}, to the branch litter compartment 0.967 kg m^{-2}, to the stem litter compartment 1.18 kg, to the coarse root compartment 1.21 kg m^{-2}, and to the fine root litter compartment 0.293 kg m^{-2}; these

values sum up to 4.22 kg C m^{-2}. The development of the input rate of C to the soil after the harvests is shown in Fig. 6a. The decomposition rates of the models were not changed during this simulation.

CBMs and SoilC model predicted the dynamics of litter in a quite similar way (Figs. 6b and 7). The amount of litter reached a local minimum in about 20 years after the harvests, increased to a maximum in about 70 years after the harvests and decreased again towards the end of the rotation period due to the decrease in the input rate of C to the soil (Fig. 6a). In general, removing harvested biomass of the site reduced the litter C storage in comparison to the equilibrium storage of the virgin site before the harvests. These dynamics of the litter C storage were regulated mainly by stem wood litter, due to its low decomposition rate and large proportion of the harvest residues and total litter after the harvests (Fig. 6a).

All three models predicted quite small changes in the amount of soil organic matter during the simulation period (Fig. 6b). However, these small changes were predicted in a different way by the different models. The amount of C in the soil organic matter compartment of CBM1 did not change notably in the simulation. This is due to the slow decomposition rate of the single soil organic matter compartment of CBM1, and the small proportion of the decomposed litter transferred to this compartment (see Table 2). CBM2 predicted somewhat larger changes in the amount of soil organic matter, due to the additional soil organic matter compartment with a higher decomposition rate and a larger proportion of decomposition in the litter compartments transferred to this compartment (see Table 2). The changes predicted by the SoilC model were even somewhat larger, and the three peaks after the harvests indicate the transfer of foliage and fine roots, branches and coarse roots and stem wood of harvest residues from the litter compartments to the soil organic matter.
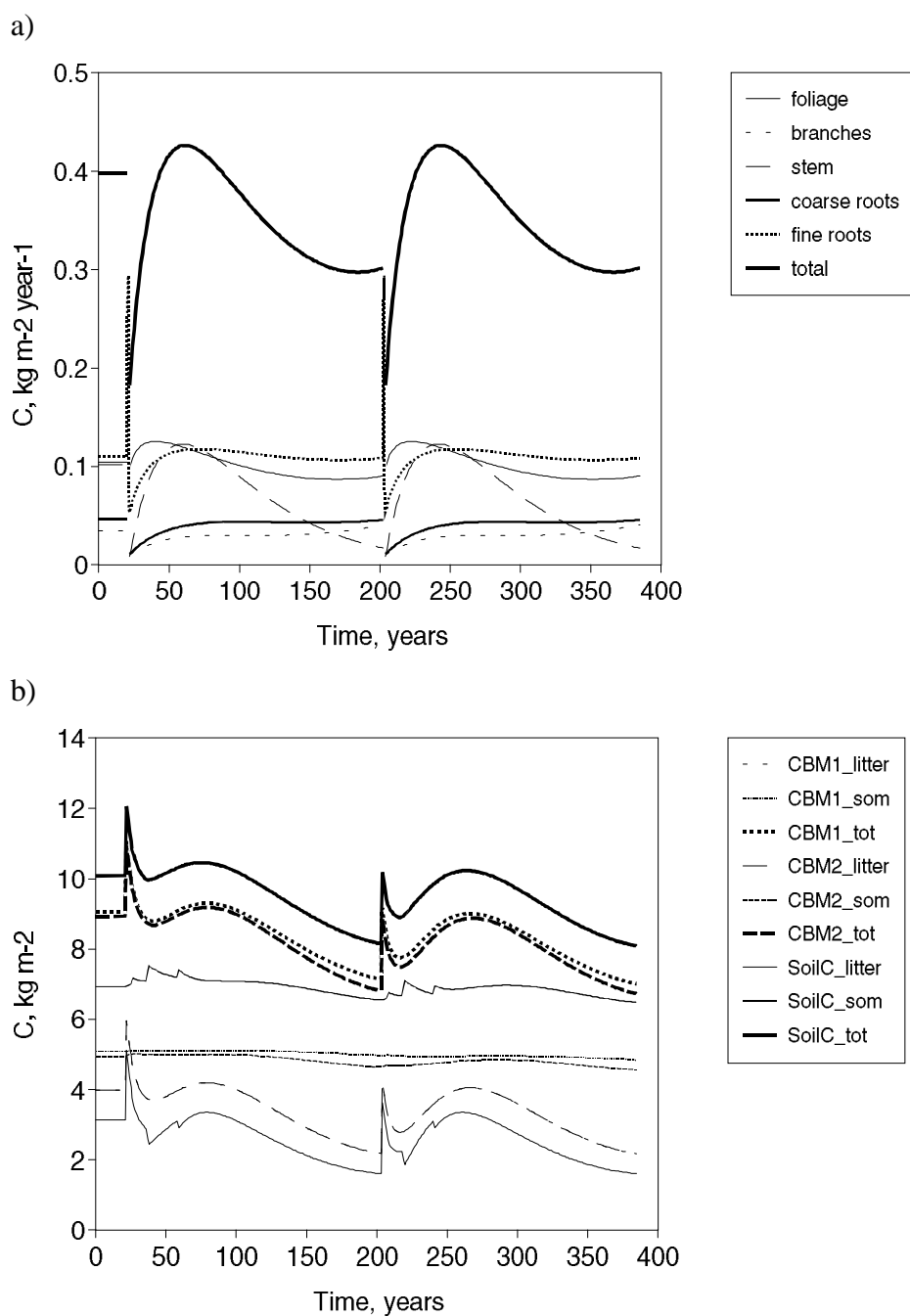
a)

b)

Figure 6. Simulation of the effects of forest harvests on the soil C storage at a pine site (site index III, density 0.6) in the Angara-Lena ecoregion using the CBM1, CBM2 and SoilC models: a) the input rate of C to the soil and b) the C storage of the litter and soil organic matter compartments of the models during the simulation. The soil C storage was run to equilibrium with the average input rate of C to the soil at a virgin site before the first harvest. At the time of the harvest, all biomass except 20% of stem biomass was added to the soil; these additions are not shown in a).
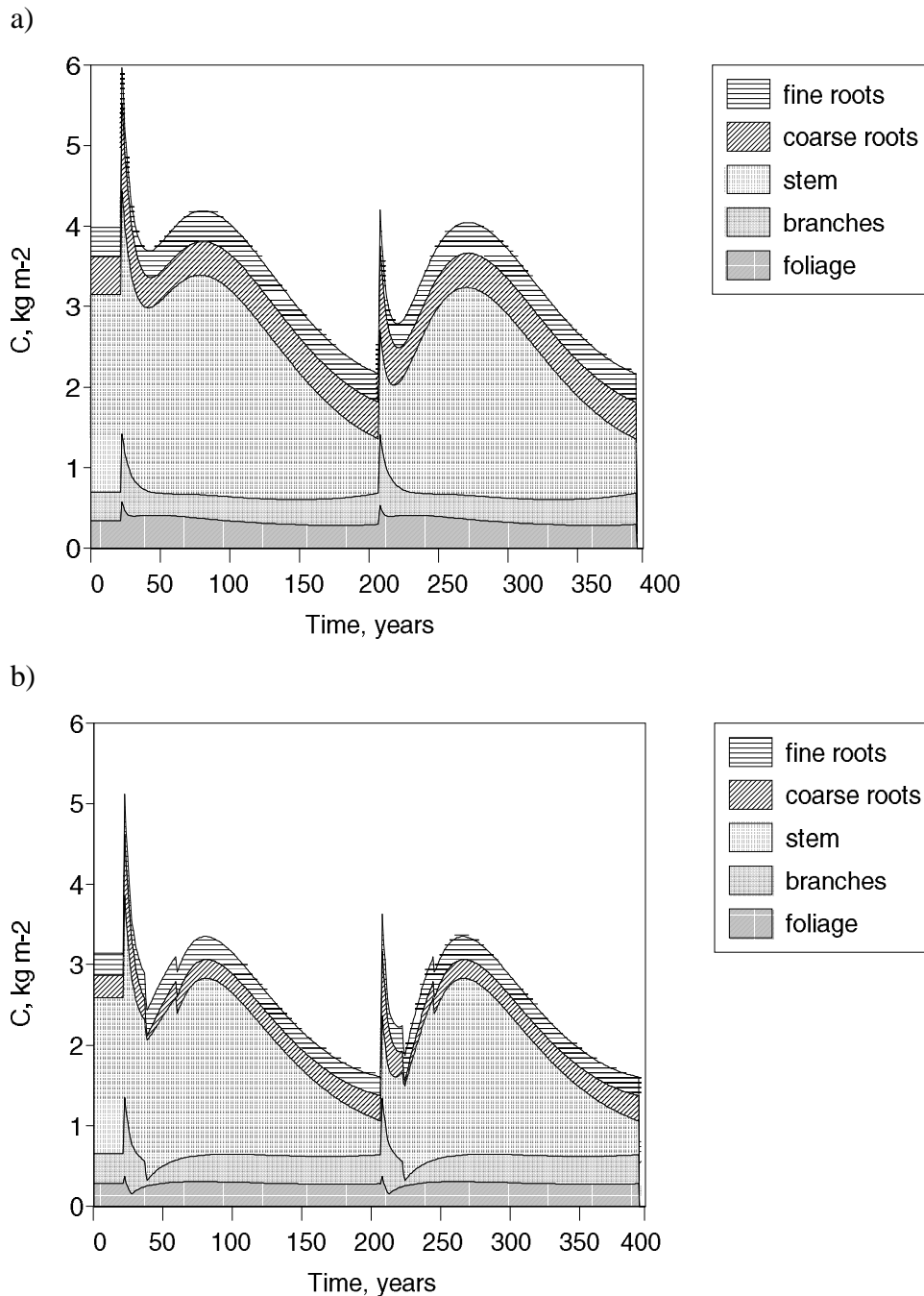
a)

b)

Figure 7. Simulation of the effects of forest harvests on the litter C storage at a pine site (site index III, density 0.6) in the Angara-Lena ecoregion using a) CBMs and b) SoilC models; this is the same simulation as in Fig. 6. Note that these charts show the litter compartments stacked so that the topmost line of all indicates the total litter C storage and the topmost line of stem litter shows the litter C storage above ground.

In these simulations the decomposition rates were kept unchanged, even if the decomposition rate of organic matter generally increases after forest harvesting, due to canopy removal and associated increases in soil temperature and moisture (Gorham *et al.* 1979). The quantity and dynamics of this increase are poorly known, but the decomposition rate may be assumed to increase to the maximum rate, which may be 25%-30% higher than the base rate, immediately after the harvest and then decrease

depending on the development of the vegetation at a specific site (Aber at al. 1978, Kurz *et al*. 1992). Taking the increase in the decomposition rate into account in the simulations of this study would not significantly affect the results. This is because, according to the growth calculations, a new stand develops quite quickly at a site and the large amount of stem litter, originating from natural mortality at the early stages of the stand development, indicates that the young developing stand is fairly dense (Fig. 6a). For this reason, it would be reasonable to increase the decomposition rates only for a short period of time, and even during most of that period the rates would be considerably lower than the potential maximum values. Furthermore, the effect on the decomposition rate of soil organic matter would be even smaller, since soil organic matter seems to be substantially more resistant to environmental conditions (see "5 Effect of climate on the decomposition rates")

7.2. Evaluation of the models for the use by the IIASA Forest Study

One of the major differences between CBMs and SoilC model is the description of the formation of soil organic matter, i.e. the transfer of C from the litter compartments to the soil organic matter compartments. In CBMs, no time is needed for the formation of soil organic matter. Because the transfer of C from the litter compartments to the soil organic matter compartments is a certain proportion of the decomposition of litter, the transfer changes at the same time as the amount of C in the litter compartments. For instance, in the simulated forest harvest above, the transfer of C from the litter compartments to the soil organic matter compartment is largest immediately after the harvest when the fresh harvest residues are added to the soil. In the SoilC model some decompositions are first needed for the formation of soil organic matter from fresh litter. If soil organic matter is defined as organic material in an advanced stage of decomposition, SoilC describes the formation of soil organic matter more realistically than CBMs. The description of the soil organic matter formation of SoilC also agrees better with the descriptions of such models in which the chemical quality of decomposing litter is followed (e.g. Aber *et al*. 1982, Pastor & Post 1986). In these models, a litter cohort remains in a litter compartment until its chemical quality, for instance nitrogen concentration, is changed over a certain limit, and the cohort is transferred to the humus compartment. In addition, from the parameterization point of view, the proportion transferred from the litter compartments to the soil organic matter compartments in the SoilC model is based on direct empirical measurements (Aber *et al*. 1990). On contrary to the CBMs, in which the transfer proportion is adjusted according to calibration data and dependent on the decomposition rate of soil organic matter.

The input rate of C to the litter compartments changes in time and in the SoilC model, the transfer from the litter compartments to the soil organic matter compartments as well the transfer between the soil organic matter compartments is dependent on the input to the compartment and the residence time. This requires a list of the past input rates in order to be able to transfer the correct amount of material after the residence time. The number of entries in such a list is equal to the residence time in years. For the litter compartments the number of entries is approximately 100 (5 for foliage litter, 20 for branch litter, 50 for stem litter, 20 for coarse root litter and 5 for fine root litter), for the first soil organic matter compartment 80 and for the second soil organic matter

compartment 900. This sums up to a list of 1080 entries per stand or stand variable object (SVO), which is the basic calculation unit in the CFS-CBM (Kurz *et al.* 1992). If the model is run simultaneously for all SVOs in the study area, the size of the list may become large. For instance, for the calculations in the Angara-Lena ecoregion about 162000 SVOs have been defined, which means a list of about 17.5 million numbers to be kept in memory.

In the case that the soil C balance calculations are performed for varying environmental conditions and the decomposition rates of the SoilC model are chosen to change in time, the list needs not only to be kept on the input rate of C to the compartments but also on the decomposition rates. Since the dependence of the decomposition of the second and third soil organic matter compartments on environmental conditions is negligible, this list needs to have the decomposition rates only for the litter compartments and the first soil organic matter compartment. The number of records in this list is thus about 180 per SVO. For the calculations in the Angara-Lena ecoregion, this would increase the number of records in the list to about 3150 million. In addition, according to the basic idea of SoilC model, the changes in the decomposition rates would also change the residence times of the litter compartments. These times can, however, be approximated for the simulations in another way than keeping a list of them for avoiding further increase in the memory requirements.

These large requirements of memory and computational resources may limit the usefulness of the present SoilC model when calculating the soil C balance simultaneously for a large number of SVOs. The SoilC model can, however, be modified to reduce the need of these resources while maintaining the basic structure of the model. Firstly, by combining the second and third soil organic matter compartments will reduce the number of values to be kept in memory by 900 per SVO. This modification does not significantly affect the accuracy of the calculations in a time scale of some hundreds of years, because the decomposition is very slow in both these compartments, these compartments are resistant to changes in environmental conditions, and, due to the delays, it takes more than 100 years until changes in the input can be observed in these compartments. Secondly, as long as the foliage and fine root litter compartments and the branch and coarse root compartments have the same parameters, they can be combined and memory for about 25 numbers per SVO can be saved. Thirdly, a longer time step than one year can be used for the stem litter compartment, because the potential changes in this compartment are slow due to the low decomposition rate. For instance, dividing the 50 year residence time into 5 year periods saves memory for 40 numbers per SVO. Making all these modifications decreases the number of values to be kept in memory from 1080 to 115 per SVO in case the decomposition rates are maintained unchanged.

In conclusion, considering the present knowledge on the cycling of C in soils, the SoilC model describes the dynamics of soil C more realistically than CBMs. In the SoilC some model transformation of fresh litter is needed before litter is converted to soil organic matter. This agrees with the definition of soil organic matter and the description of the formation of soil organic matter in more detailed models. In addition, the transfer proportion has stronger empirical basis than the transfer proportion of CBMs. On the other hand, SoilC requires more computational resources than CBMs, even if these requirements can be considerably reduced by simple modifications of the model. However, if the number of SVOs is very large, these

resources may prevent the use of SoilC model. In this case CBM2 can be recommended rather than CBM1, because CBM2 describes the dynamics of soil C in a more flexible way than CBM1 and predicts the dynamics of soil organic matter closer to the SoilC model (see Fig. 6b).

8. Applications by the SoilC model

8.1. Storage of organic C in the soil of coniferous and deciduous forests in the Angara-Lena ecoregion

Equilibrium soil C storages were calculated for a pine (site index III, density 0.6) and a birch site (site index III, density 0.6) in the Angara-Lena ecoregion for investigation of the differences in storage under coniferous and deciduous vegetation. For the pine site, the equilibrium storage was calculated by using the input rates of C to the soil at a virgin site, as has been described earlier under "7.1 Simulation of forest harvesting". For the birch site, the input rate was calculated in a similar way: the total biomass production during 120 years was divided by the length of this period for the average annual input rate of C to the soil. This shorter period of 120 years was chosen for the birch site instead of 180 years which was used for the pine site, because birch stands do not generally grow as old as pine stands and the equations of birch stand production were not valid for stands older than 120 years (Karjalainen 1997). Also, unlike the pine site, all above-ground production of ground vegetation was merged with the foliage litter compartment and all below-ground production of ground vegetation to the fine root litter compartment. This can be justified by the fact that the relatively small amount of ground vegetation at birch sites was thought to be comprised mainly by grasses and small shrubs instead of understory trees, which are common at pine sites (Karjalainen 1997). Consequently, the average input rate of C to the soil at a virgin birch site was approximated to be 0.306 yr^{-1}, of which 0.104 kg m^{-2} yr^{-1}, 0.0342 kg m^{-2} yr^{-1}, 0.0726 kg m^{-2} yr^{-1}, 0.0506 kg m^{-2} yr^{-1} and 0.0447 kg m^{-2} yr^{-1} was put to the foliage, branch, stem, coarse root and fine root litter compartments, respectively.

The equilibrium soil C storage totaled 9.45 kg m^{-2} at the pine site and 30% less, 6.62 kg m^{-2}, at the birch site (Table 4). For the C storage of litter this difference was 44% and for the C storage of soil organic matter compartments 23%. This difference in the C storage of soil organic matter is solely due to the 23% smaller input rate of C to the soil at the birch site. The decomposition rates of the soil organic matter compartments were the same for both tree species and the equilibrium storages are directly proportional to the input rate. In the litter C storage the difference is additionally caused by the higher decomposition rate of litter at the birch site. At both types of sites, about one third of the total soil C storage was comprised of litter and two thirds of soil organic matter. More than 40% of the total soil C storage was in soil organic matter compartments 2 and 3 indicating that this C is more than 100 years old.

Table 4. Estimated soil C storage at virgin pine (index III, density 0.6) and birch sites (index III, density 0.6) in the Angara-Lena ecoregion by using the SoilC model.

Model compartment	Pine site		Birch site	
	kg m^{-2}	%	kg m^{-2}	%
Foliage litter	0.27	3	0.16	2
Branch litter	0.28	3	0.20	3
Stem litter	1.96	21	1.06	16
Coarse root litter	0.38	4	0.30	5
Fine root litter	0.29	3	0.07	1
Litter subtotal	3.19	34	1.79	27
Soil organic matter 1	2.36	25	1.81	27
Soil organic matter 2	2.80	30	2.16	33
Soil organic matter 3	1.10	12	0.85	13
Soil organic matter subtotal	6.26	66	4.82	73
Total	9.45	100	6.62	100

For comparing the effects of forest harvests on the soil C storage at coniferous and deciduous sites, similar kind of forest harvests were simulated for a birch site (site index III, density 0.6) as for the pine site earlier under "7.1 Simulation of forest harvesting". However, in the simulation of the birch site the interval between the subsequent harvests was 120 years instead of 180 years used for pine sites. The input rate of C to the soil used in the simulation is shown in Fig. 8a. Like in the simulation of the pine site, the decomposition rates were kept constant in this simulation.

The forest harvests reduced the C storage of litter at the birch site a little more than at the pine site, but the litter C storage also recovered more quickly at the pine site, within some 50 years following the harvests (Figs. 6b and 8b). These more pronounced and faster dynamics of the litter C storage at birch sites were due to the higher decomposition rates of birch litter in general, but also due to the smaller proportion of slowly-decomposing stem litter of the total litter C storage (Figs. 7b and 9). The dynamics of the C storage of soil organic matter were quite similar at the birch and pine sites (Figs. 6b and 8b), due to similar decomposition rates of the soil organic matter.
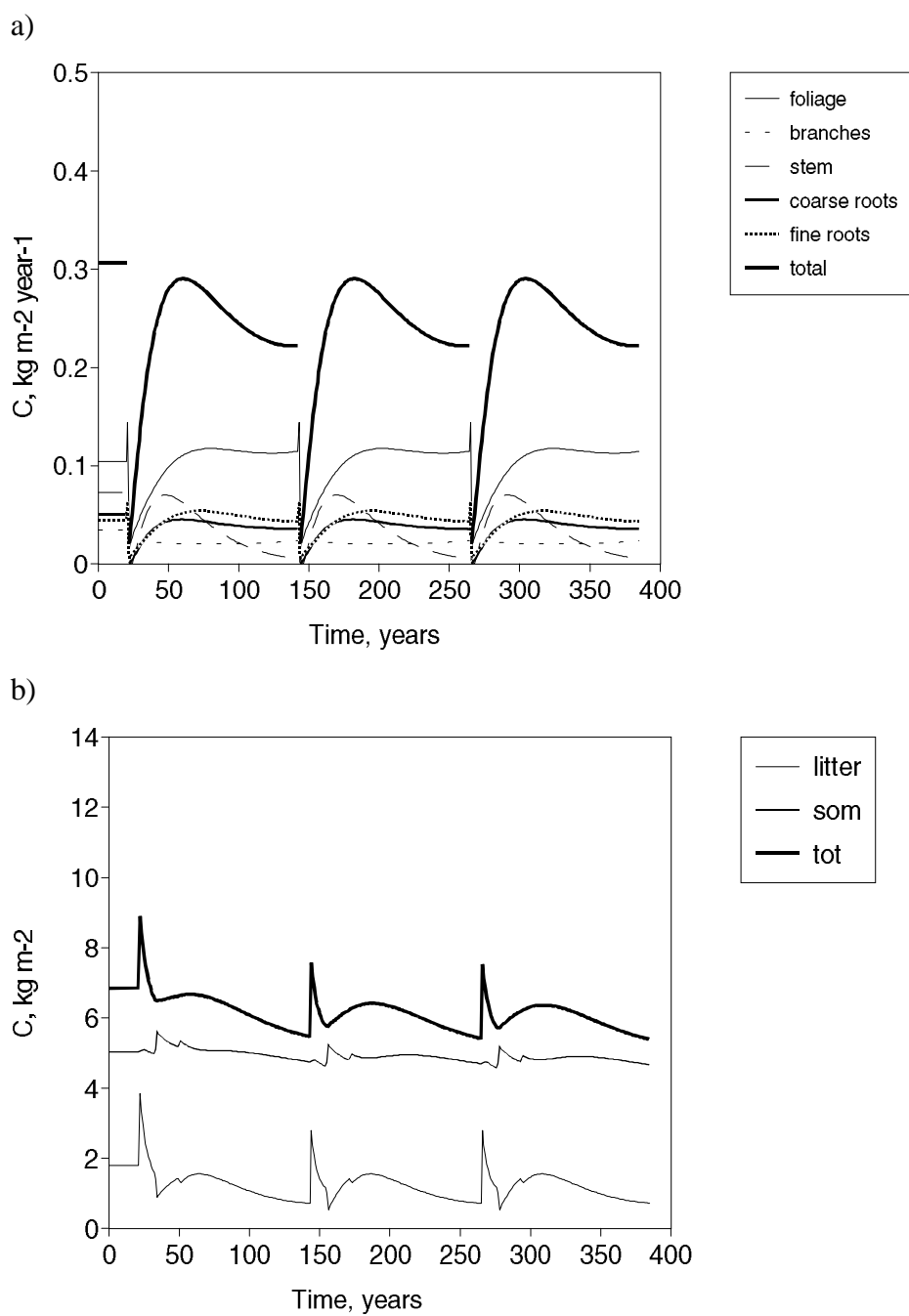
a)

b)

Figure 8. Simulation of the effects of forest harvests on the soil C storage at a birch site (site index III, density 0.6) in the Angara-Lena ecoregion by using the SoilC model: a) the input rate of C to the soil and b) the C storage of the litter and soil organic matter compartments of the model during the simulation. The soil C storage was run to equilibrium with the average input rate of C to the soil at a virgin site before the first harvest. At the time of the harvest all standing biomass except 20% of stem biomass was added to the soil; these additions are not shown in a).
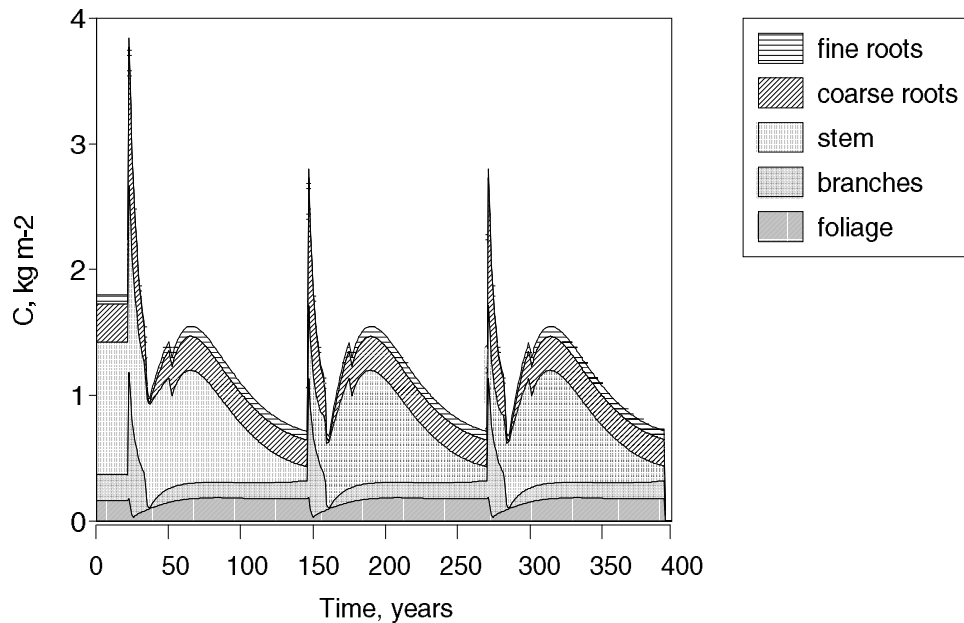
Figure 9. Simulation of the effects of forest harvests on the litter C storage at a birch site (site index III, density 0.6) in the Angara-Lena ecoregion by using the SoilC model; this is the same simulation as in Fig. 8. Note that these charts show the litter compartments stacked so that the topmost line of all indicates the total litter C storage and the topmost line of stem litter shows the litter C storage above ground.

8.2. Effect of harvesting intervals and the amount of harvest residues on the storage of organic C in soil

For studying the effect of harvesting intervals on the soil C storage, a similar kind of subsequent forest harvest were simulated for a pine site (site index III, density 0.6) as before, but the time between the harvests was reduced from 180 years to 100 years. This harvest interval is recommended for these kind of pine sites in the Angara-Lena ecoregion (Charles Backman pers. comm.). The effect of the amount of harvest residues left at the site was investigated by leaving either 20% or 60% of the stem wood at the site in the simulation. This range of harvest losses is common in Siberia (Shvidenko & Nilsson 1994). Like in the earlier harvest simulations, all other biomass was added to the respective litter compartments at the time of harvesting.

Harvesting at the interval of 100 years did not significantly affect the soil C storage over the simulation period (Fig. 10). This is different from the simulation of harvests at the interval of 180 years, in which the removal of biomass from the site caused a decreasing trend in the soil C storage (Fig. 6b). When harvesting at the shorter interval, the removal of C from the site in the harvested biomass was compensated by the increased mean amount of C added to the soil over a rotation period. The increase in the amount of C added to the soil was, in turn, caused by avoiding the low rate of C input to the soil in overmature stands (Fig. 6a). Instead, the large amount of slowly-decomposing C in stems dying at the stand age of around 40 years was added to the soil more frequently. If these stems were removed of the site in thinning harvests, which would have been the aim by intensive forest management, the thinnings would have unlikely increased the production of the remaining stand enough to compensate

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for this C loss of the site. Even if these results enable interesting speculations about managing forests for soil C, it is worth emphasizing that these effects of the length of the rotation period are entirely dependent on the period used for calculating the input rate at a virgin site. If the input rate of a virgin site was calculated on the basis of 100 year period, harvesting and removal of biomass at the same interval would naturally lead to a decrease in the soil C storage, because less C would reach the soil due to the harvesting.
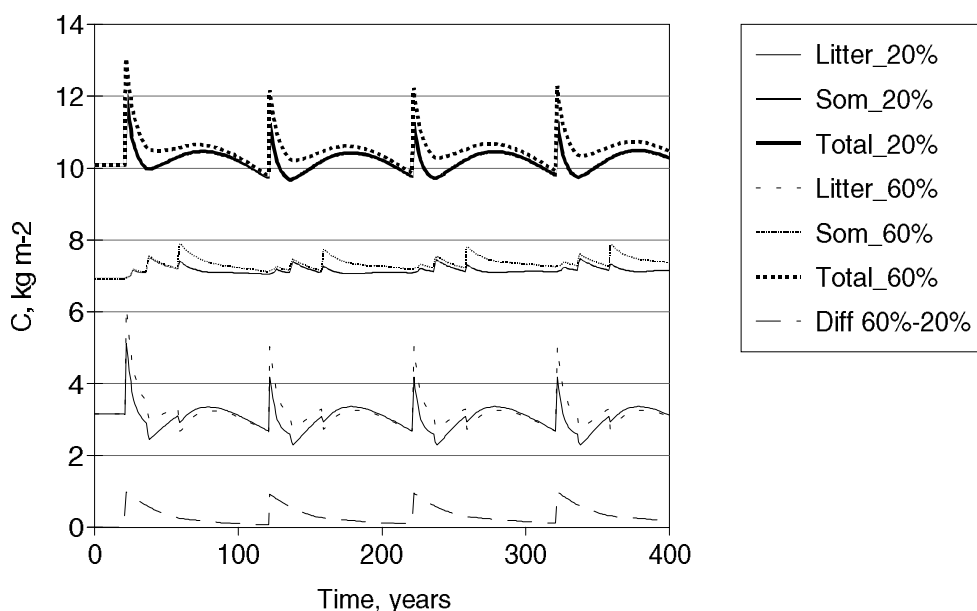

Figure 10. Simulation of the effects of harvesting at 100 year intervals and the amount of harvest residues left at the site on the soil C storage at a pine site (site index III, density 0.6) in the Angara-Lena ecoregion by using the SoilC model. The soil C storage was run to equilibrium with the average input rate of C to the soil at a virgin site before the first harvest, and at the time of the harvest all standing biomass except 20% or 60% of the stem biomass was added to the soil. Diff 60%-20% represents the difference in the total soil C storage between the simulations leaving 60% or 20% of the stem biomass.

Leaving 60% of the stem biomass at the site instead of 20% affected the soil C storage naturally most at the time of harvesting, and then the difference in the C storages was equal to the difference in the amount of C in the stem wood left at the site (Fig. 10). When the soil C storage was as smallest, about 20 years after the harvests, the total soil C storage was some 0.6 kg m^{-2} smaller, i.e. 6% of the storage at that time, in the case that 20% of the stemwood was left at the site instead of 60%. Over the whole rotation period, the average soil C storage was only 3% larger when leaving 20% of the stem biomass instead of 60%. The reason for this small overall effect of the harvesting efficiency on the soil C storage is that even by 60% of the standing stem biomass left at the end of the rotation period, some 3 kg C m^{-2}, corresponds only to about 7% of the total amount of C added to the soil over the rotation period. According to these results, improving the efficiency of harvesting in Siberian forests would not significantly affect the amount of C stored in the forest soils.

9. Conclusions

In this study, three models describing the dynamics of organic C in forest soils were compared. The SoilC model was judged to describe the dynamics of soil C in the most realistic way, and is, therefore, recommended for the calculations of the soil C balance by the IIASA Forest Study. The CBM2 model predicted quite similar dynamics for soil C, and is recommended for the calculations in the case computational resources limit the usefulness of the SoilC model.

Temperature was considered to be the most important climatic factor that regulates the decomposition in the boreal forests. Decomposition of soil organic matter was found to be far less sensitive to temperature than the decomposition of litter. In other words, using the same temperature dependence for decomposition of soil organic matter as for litter would significantly overestimate the effect of temperature on decomposition as a whole. The effective temperature sum with a $+5°C$ threshold was chosen to describe the temperature impact. Equations, which can be used for calibrating the models for the temperature sums ranging from 470 to 2210 degree-days, are given. Reference decomposition rates of these equations were collected from literature for the litter of coniferous and soft deciduous species.

As examples on the potential applications of the models, the SoilC model was used for studying the effects of tree species, harvesting intervals and the amount of harvesting residues on the soil C balance at a stand level. The equilibrium soil C storage was about 30% smaller at a birch site than at a pine site. Also the dynamics of the litter C storage were faster and more pronounced at the birch site due to a faster decomposition of litter. Increased harvesting intervals increase the actual productivity of a site, which compensates for the loss of C by the removed harvested biomass. In fact, it may even lead to some accumulation of additional C to the soil. The amount of harvest losses, i.e. amount of harvested stemwood left on the site, did not significantly affect the average soil C storage, because the quantity of C of the harvest losses is small in comparison with the quantity of C brought to the soil by other vegetation over the total rotation period. Consequently, increased efficiency in the forest harvests in Siberia would unlikely cause significant decreases in the soil C storage of the forests.

The SoilC and CBM2 models seem in principle applicable for calculating the C balance of upland forest soils at the ecoregional level in Russia. Even if forest fires, which are important natural disturbances in Russia (Shvidenko & Nilsson 1994), were not investigated in this study, they can be simulated with the models quite easily. Consideration of the effects of drought on decomposition and perhaps adding a moisture factor to regulate decomposition aside temperature would improve the accuracy of the calculations in regions where the lack of moisture may limit the decomposition.

Most importantly, however, calculating the C balance for most of the ecoregions in Russia, the special features of permafrost soils and peatlands need to be added to the current models, because such soils are very common in Russia (Moroz 1996, Rozhkov *et al*. 1996) and they play a particularly significant role in the C balance of forest soils in Russia as a whole. The accumulation and very slow decomposition of C in the anaerobic layers of peatlands can probably be described in the models by either

adding a compartment with a very slow decomposition rate or decreasing the decomposition rate of the last soil organic matter compartment. For modeling the dynamics of C in permafrost soils, a comprehensive literature review of the approaches used earlier in other studies would be helpful. It should, however, be kept in mind that whatever approach will be chosen, there need to be enough information for properly parameterizing and testing of the chosen approach for Siberian conditions. In addition, the level of detail of the soil C balance calculations should be in agreement with the calculations of the vegetation C balance, because it is from these vegetation calculations the soil C calculations receive the input.

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