Carbon in Pine Forest Ecosystems of Middle Zavolgie, Russia

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ABSTRACT

Beginning with the industrial revolution, the rapid increase in atmospheric CO_2 concentrations still continues to give rise to concern about a long-term global climate change. Being large reservoirs of carbon, the pine forests of Middle Zavolgie are an important part of Russian forests and, thus, of the global carbon cycle.

The aim of this study is to estimate the carbon budget for pine biomass at the stand and regional levels in Middle Zavolgie, Russia. The assessment is based on carbon sequestration. This approach enables studying the remaining amount (subtracted from the gross production) of carbon in vegetation, litter, and soil organic matter after the carbon has been released back into the atmosphere by the respiration and decay processes.

The total carbon budget during a period of 120 years for the I site modal pine stands is 160 Mg C/ha, consisting of vegetation stock 107 Mg C/ha, litter stock 28 Mg C/ha and SOM stock 28 Mg C/ha. The largest total stock of 254 Mg C/ha consists of a normal pine stand of the first site.

The total regional carbon budget of pine forests is 128.4 TgC. While Kirovskaya oblast has the largest proportion of the total carbon stock in Middle Zavolgie (70 TgC), Tatarstan has only 5.2 TgC. The pine stands of Nizegorodskaya oblast and the Mari El Republic have 37.4 TgC and 15.8 TgC of carbon stores, respectively.

This study on the stand level analysis forms the basis for a further method of regional assessments. However, when calculating accurate estimates, several factors should be taken into account. These include stand structure, forest fires, and other disturbances, including the removal of biomass from the forest as wood-based products.

Keywords: pine forests, carbon budget, global warming, forest mensuration, Russia

ABBREVIATIONS

Pg – petagram = 10^{15} g	N – dry mass of needles
Tg – teragram = 10^{12} g	R- correlation coefficient
Mg – megagram = 10^{6} g	V – stem volume
C – carbon	Ha – hectare
CO_2 – carbon dioxide	U_n – dry mass of undergrowth
B.A. – basal area	S_h – dry mass of shrubs
H – average height of the forest ecosystem fraction	F-ratio – Fisher's criteria
D – tree diameter at the breast height	F_l – dry mass of forest floor
L_{cr} – length of crown	R_v – ratio of forest phytomass
D_{cr} – diameter of crown	Wd – woody detritus
A – stand age	R^2 – R-squared statistic

1. INTRODUCTION

There is no doubt that human pursuits have caused a considerable increase in the atmospheric concentration of CO_2. According to comprehensive atmospheric records data from sites of Mauna Loa (USA Scripps Institution of Oceanography), CO_2 concentrations have been growing steadily for the past 40 years. The Mauna Loa record shows a 12.8% increase in the mean annual concentration, from 315 parts per million by volume (ppmv) of dry air in 1959 to 356 ppmv in 1992 (Trends 1993).

The Intergovernmental Panel on Climate Change in Brazil (Houghton et al. 1992) concluded that the increase in greenhouse gas concentration in the atmosphere and the consequent enhancement of the greenhouse effect would result in global warming. That, in turn, according to the pessimistic prognosis, could result in the melting of polar ice, more frequent floods, droughts and forest fires.

There are alarming signs that the climate change has already begun. Nature has started to react to the ongoing warming induced by the greenhouse effect, as can be seen from the migration of many plant and animal species to higher altitudes. Warmer weather also increases the number of thunderstorms, tornadoes and strikes by lightning (Houghton 1997).

However, considerable uncertainty prevails of the effects that these changes will have on global climate. For example, a review of the climate across the continental US has revealed that winters in the period from 1975 to 1983 were either much warmer or much colder than normally (Houghton 1997). A computer climate modelling has also shown that six abnormal winters in a period of eight years is very rare, occurring only once every 1100-1250 years. The writers suggest that in a reasonably stationary climate, a series of extreme years preceded by a period of 60 years of normal variability is either unusually rare, or marks a shift towards a climate change.

It is predicted that considerable changes will take place in northern latitudes, which are mostly covered by boreal forests. As for the size of carbon (C) production and the duration of its sequestration, the forest ecosystems of the planet are considered the most reliable system, which may help in the mitigation of enhancing the greenhouse effect. In fact, several assessments (Tans et al. 1990; Sedjo 1992; Kauppi and Tomppo 1993 and Dixon et al. 1994) show that forests in the temperate and boreal zones have functioned as carbon sinks for the past few decades.

Carbon has been accumulating in the atmosphere ever since the large-scale exploitation of forests began. During the last 100 years, carbon accumulation has been enhanced considerably due to the increasing use of fossil fuels. Changes in land use and land management, especially deforestation, cause significant changes in terrestrial carbon stock, resulting in a flux of CO_2 from land to the atmosphere. Carbon that used to be bound in forests has been released back into the atmosphere. Yet, the growth of the remaining forests and the uptake by the oceans have not been able to absorb all this “additional” carbon (Houghton et al. 1990).

Forest ecosystems dominate the gross annual biogenic flux between the atmosphere and the terrestrial biosphere. The global terrestrial net primary productivity has been estimated at, roughly, 60 Pg/yr. Recent estimates of the global C cycle indicate that combustion of fossil fuels accounts for 5.5 ± 0.5 Pg C/a (Pg = 10^{15} g) and changes in land use and deforestation for 1.6 ± 1.0 Pg C/a of the total net anthropogenic sources of 7.1 ± 1.1 Pg C/a (Schimel 1995). The uptake by the ocean is estimated to be 2.0 ± 0.8 Pg C/a, and the accumulation in the atmosphere 3.2 ± 0.2 Pg C/a.

It is important to study the C sequestration of forest ecosystems, because they contain over 75% of the carbon accumulated in terrestrial vegetation (Olson et al. 1983). Changes in this reservoir are large enough to affect the global climate (Smith and Shugart 1993). On the other hand, the predicted climate change may alter the productivity of forest ecosystems, thus altering their ability to sequester carbon. The increasing CO_2 concentration in the atmosphere also tends to increase the growth of vegetation, at least in the short term (Houghton et al. 1992).

It is well known that at the expense of improving the methods of forest growing, the optimisation of age and species structure of forest ecosystems and additional reforestation of the areas, there is an opportunity to sequester a certain amount of CO_2 from the atmosphere into phytomass. In connection with the above, humankind, on the border of the third millennium, is coming to a new ecologically oriented paradigm in its utilisation of forest ecosystems. This, due to the development of new trends in forest management, will undoubtedly require reconsideration of various aspects of the forest utilisation and growing policies.

The expected warming has been estimated to alter the distribution of vegetation over the globe, especially in the boreal and temperate zones (Smith et al. 1992; Monserud et al. 1993). Because boreal forests are a large carbon reservoir and located in latitudes predicted to undergo the greatest warming, they may play an essential role in future carbon fluxes (Dixon et al. 1994).

Unlike the forest ecosystems of the tropical and subtropical zones, the boreal forests of higher latitudes are formed of a small number of tree species and characterised by a slow biological cycle. The amount of annual fall of plant residues in these ecosystems predominates over the annual norm of their decomposition. In connection to this, boreal forests accumulate carbon not only in the wooden biomass, but also in litter, coarse woody debris (woody detritus), soil organic matter and peat.

Russia has approximately 30% of the world’s boreal forests (Murray 1993) and, together with Canada and the USA, it is known to be one of the largest carbon reservoirs on earth. Therefore, the estimation of the carbon budget for the territory of Russia is urgent for the international strategies that aim at mitigating the consequences of the predicted global climate change.

A number of large research centres has evaluated and estimated the organic carbon stocks in the forest ecosystems of Russia by applying different methods. However, the results of these researches frequently contradict each other (Table 1).

This divergence may occur, because the calculations of the global carbon balance are generally carried out through a data extrapolation of a limited number of sample data on the phytomass on a rather vast territory. Therefore, in order to receive true and correct data of the carbon balance of the forest ecosystems of Russia, research should be carried out at a regional level with accurate data of particular and specific experimental works that take into account all the above-mentioned factors on the territory of separate forestry enterprises. This kind of research would contribute much to the development of ecologically substantiated and proven strategy of nature utilisation at the level of economic region.

The role of forest in the predicted climate change brings about pressing demand to study and investigate this very problem, for example, in Russia, in close co-operation and collaboration with European countries familiar with this problem. This kind of research, in particular, is expected to become of considerable theoretical and practical interest on the territory of Middle Zavolgie.

Table 1. Compilation of carbon pools and pool change estimates in the boreal forest zone of Russia (Karjalainen 1996).

Year	Biomass, Tg	Soil, Tg	Total, Tg	Average C density, Mg/ha	Net sequestration, Tg/a	Source
1988	42100		45000	51		a
1988	50403	349534	399937	500	853	b
Late 1980s	44000	117000	161000	246	410	c
	35070		35070	41	213	d
	27980	90848	118828	154		e
1993	33900		33900	38		f
		320635	320635	360		g

a) Krankina et al. 1996, b) Kolchugina et al. 1993, c) Kolchugina and Vinson 1995, d) Isaev et al. 1995, e) Alexeyev and Birdsey 1994 f), Shvidenko and Nilsson 1996, g) Rozhkov et al. 1996

2. THE AIM OF THE STUDY

The aim of this study is to examine C sequestration in pure pine stands under the current climatic conditions at stand and regional levels in the region of Middle Zavolgie in Russia. Ecosystem components that will be considered in the assessment will include total tree biomass, understorey (undergrowth, shrubs, and forest floor), litter, and soil organic matter (SOM). The assessment will be based on total carbon sequestration, i.e., the amount of carbon that is left in vegetation, litter, and soil organic matter, when its flow back into the atmosphere (through the respiration and decay processes) is subtracted from the gross production.

Currently, when carrying out forest assessment works in the region of Middle Zavolgie, it is common to use *normal* pine stands that presume natural, fully stocked and unmanaged forest ecosystems. Such forest stands occur infrequently in nature and serve mainly for simulations of yield and growth tables. At present, the main forest ecosystems in the region are *modal* stands, which are mostly managed and disturbed, and have less stand density and stock than unmanaged ecosystems.

Both normal and modal pine forest ecosystems on the investigated territory have been used in further calculations that take into account all types of forests. The investigation of normal and modal pine stands forms the basis for understanding the dynamics of C sequestration for the conditions of Middle Zavolgie and the carbon budget simulations.

3. FOREST GROWTH CONDITIONS IN MIDDLE ZAVOLGIE

3.1 TERRITORY

Middle Zavolgie (Figures 1 and 2) is located in the eastern part of the Russian plain, where it covers 287000 km^2. The region subsumes to the Volgo-Vyatski and Povolzskij economy areas in the economy republic classification of the Russian Federation. The administrative units in this territory are the Republic of Mari El, Tatarstan and the Nizegorodskaya and Kirovskaya oblasts.

Middle Zavolgie can be subdivided into three ecological zones: taiga (southern part), mixed forest and forest-steppe (Figure 3). The Volga River serves as the natural physiographic western border. The territory north to the line Volga – Kazan – Right Bank of Kama up to the eastern border of Tatarstan belongs to the zone of mixed forest. The zone of forest-steppe is located to the south of this line. The northern part of Kirovskaya oblast belongs to the taiga zone.

The land surface of the territory is hilly plain, the height variations being almost unnoticeable (from 45 to 275 m above the sea level), and the transitions from the lower to the higher parts being quite gradual. The highest parts are located in the south-eastern part of the region. From there, the surface descends towards the Volga River valley. Along the river, the central lowland extends as a wide band with a large number of lakes, marshes and rivers. The high right bank rises above the valley of the Volga River in the form of a steep ledge with deep ravines and gullies.

3.2. CLIMATE

Middle Zavolgie is located at an almost equal distance of more than one thousand kilometres from the southern, western and northern seas and oceans. Nevertheless, only the air masses from the Atlantic and the Arctic Ocean considerably influence the climate of the region.

The climate of Middle Zavolgie is, thus, not only determined by its continental location as a flat relief, but also by the rotational impacts of the air masses from the Atlantic and Nordic oceans and the dry continental masses from Kazakhstan and Central Asia.

Temperature rises from south to north, because the disposition changes of temperature and the absorbed radiation with latitude direction are nearly identical. The amount of precipitation with latitude is more irregular in winter than in summertime (Table 2). In summer, the distribution of precipitation with latitude is more stable (Frenkel 1997).

The climate does not coincide with calendar seasons. The criterion for the change of a climatic season is the transition of the average daily temperature over a certain boundary (Frenkel 1997). According to such a criterion, November and March are winter months.

Winter is considered to begin, when the stable changes of the average daily temperatures remain below 0^0C, and a blanket of snow covers the earth and ice appears on rivers. This happens in the period between the end of October to the first week of November. Winter ends at the end of the first week of April. Thus, the duration of winter is about 160 days (Table 2).

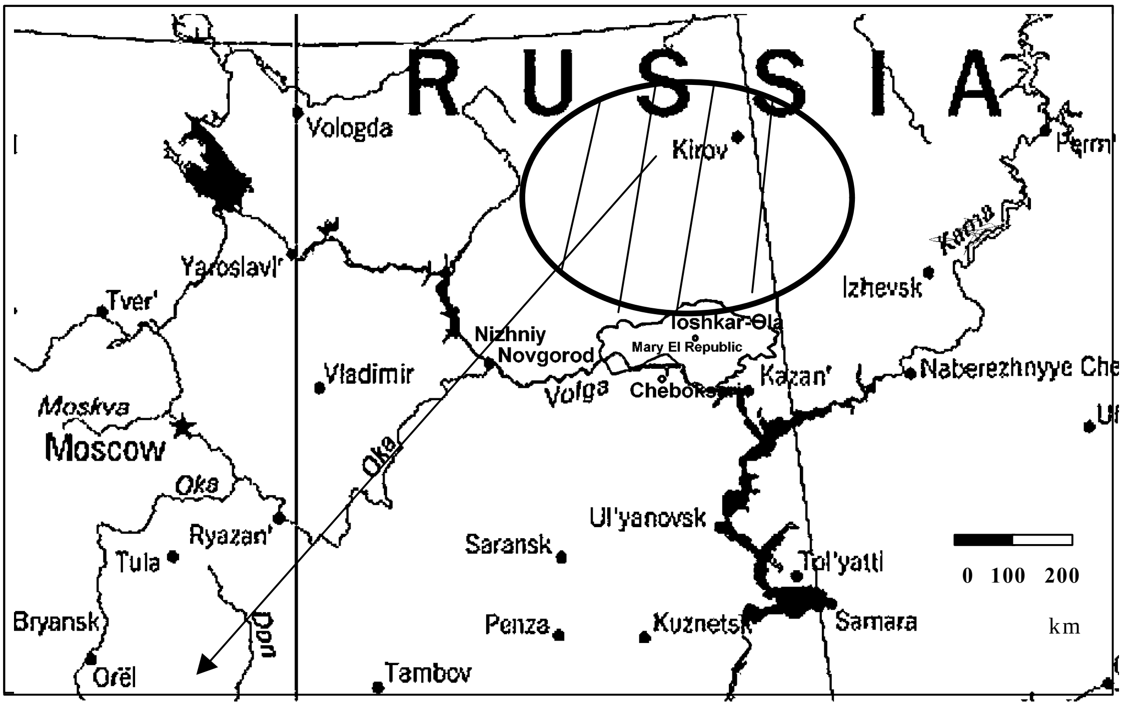

Figure 1. Middle Zavolgie on the map of Russia.

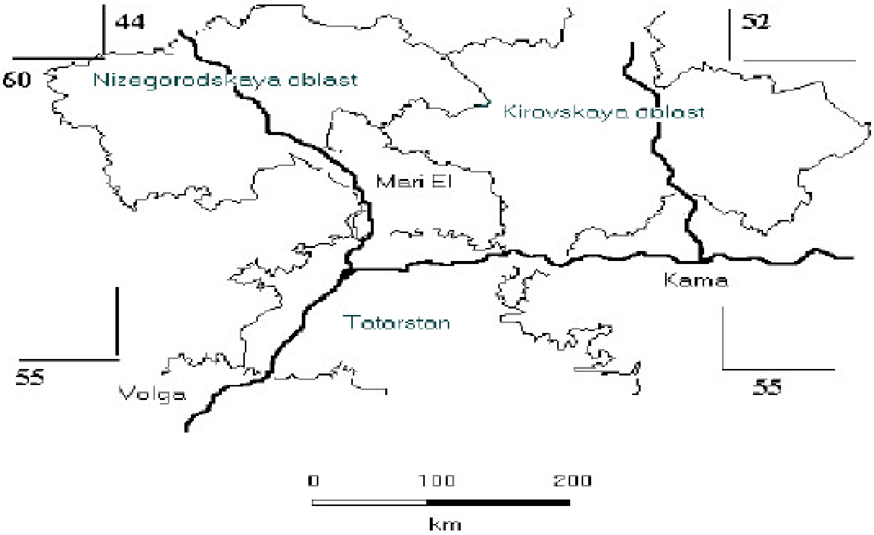

Figure 2. Administrative areas in Middle Zavolgie.

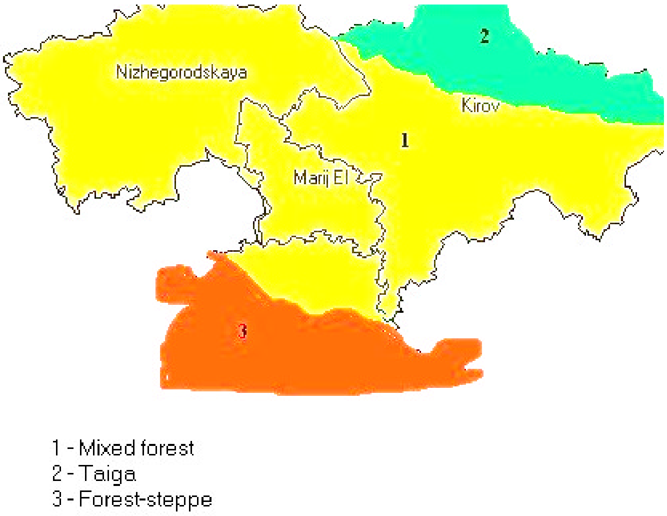

Figure 3. The forest growth zones of Middle Zavolgie.

Spring comes in the first week of April, with the stable transition of the average daily temperature above 0^{0}C, and ends at the end of May - first week of June, with the temperature transition above 15^{0}C. As a result, the duration of spring is about 60 days.

Summer is considered to begin at the end of May - first week of June, with the temperature transition above 15^{0}C. Summer ends, when the temperature transition settles over 10^{0}C after the discontinuing of active vegetation. For most of the territory of Middle Zavolgie, this happens 11-20 September. The duration of summer is, thus, 90 days.

The transition of the average daily temperature below 10^{0}C marks the beginning of autumn, and below 0^{0}C, the end. Usually this period starts in the second week of September and lasts until the end of October. In other words, the duration of autumn is about 40 days.

The climate of Middle Zavolgie is considered to be temperate-continental with a relatively stable weather in winter and summer, but considerably changing conditions in spring and autumn.

The mean annual temperatures vary from $+2.2^{0}$ C in the north-eastern regions, up to $+3.1^{0}$ C in the south-west. A distinct tendency of the change of mean annual temperatures in lower atmospheric strata has been observed during the last 66 years (1930-1996) towards warming (Figure 4). In recent years, winter months have been warmer than earlier (Kurbanov and Yakovlev 1998).

Table 2. The duration of seasons, average temperatures and precipitation in the Middle Zavolgie (Frenkel 1997).

Weather Station	Duration of the season, days	Temperature, ^{0}C			Precipitation, Mm
		t_{mean}	t_{max}	t_{min}	
Summer					
Kirov	91	16.2	37	-2	209
Kazan	110	17.9	38	-1	195
Yoshkar-Ola	101	16.8	39	-3	190
Nizni Novgorod	105	17.2	36	-2	200
Autumn					
Kirov	41	5.2	29	-23	123
Kazan	45	7.3	32	-17	104
Yoshkar-Ola	47	6.5	31	-19	114
Nizni Novgorod	40	7.3	31	-16	108
Winter					
Kirov	170	-10.3	12	-45	167
Kazan	152	-9.5	15	-47	135
Yoshkar-Ola	164	-9.5	15	-47	151
Nizni Novgorod	158	-7.9	16	-41	172
Spring					
Kirov	63	5.2	29	-23	123
Kazan	58	7.3	32	-17	104
Yoshkar-Ola	60	6.5	31	-19	114
Nizni Novgorod	63	7.3	31	-16	108

According to the data of the Kazan meteorological station (Perevedencev 1998), during the 19th and 20th centuries, linear trends of temperature ($y = Ax+B$) had positive A coefficients. Of all months, the highest temperature growth (warming) was registered in December and January (Table 3).

The most significant temperature deviations have occurred in the cold period of the last two decades (1978-1987, 1988-1997). The months of February in the last decade show a record-breaking rise in temperature in the period of the last two centuries: $\Delta t= 3.29^0$C ($\Delta t= t_1 - t$, where t_1 is the mean temperature of any decade, and t the normal temperature of the decade in question). Undoubtedly, it confirms the unsustainability of the recent climatic developments.

Table 3. The trend parameters of the decennial average temperatures. A and B are trend coefficients.

Month	A	B
I	0.21	-14.88
II	0.13	-13.06
III	0.20	-7.63
IV	0.21	2.20
V	0.13	11.63
VI	0.11	16.72
VII	0.04	19.52
VIII	0.05	17.16
IX	0.10	10.48
X	0.08	3.29
XI	0.07	-4.06
XII	0.25	12.6
Year	0.13	2.39

The average amount of precipitation is 450-500 mm, of which 250-300 mm falls during the vegetation period (spring and summer). On the whole, Middle Zavolgie is located in the zone of unstable moisture: years and seasons with sufficient, and sometimes even with excessive moistening, are coupled with dry ones.

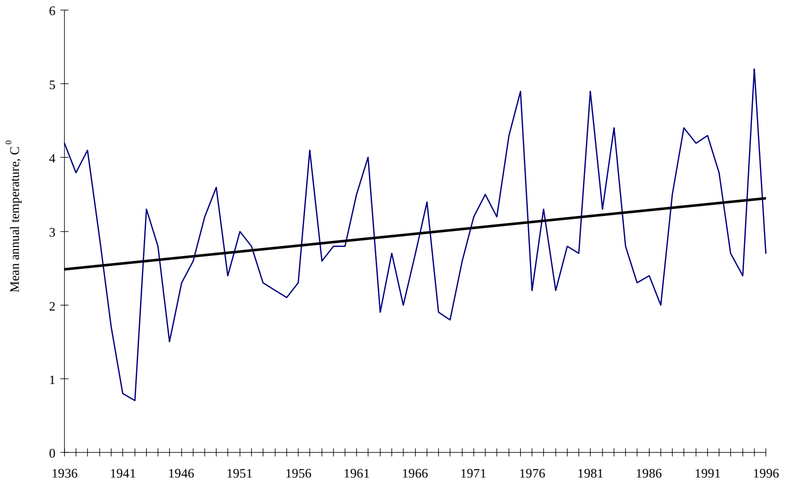

Figure 4. Development of the annual mean temperature since 1930, trend is 0.60 / 60 years (Data of Yoshkar-Ola Metereological station, 56.38°N, 47.55°E).

3.3 THE SOIL

In congeneric climatic conditions, the type of soil plays the principal part in determining the type of the forest ecosystem emerging in the area.

There are mainly sandy and sandy loam soils in the left backside of Volga, its eastern part consisting of loam, turf-carbonate, brown-gray and turf-ashen-gray forest soils. Most spread soils in the taiga zone of Middle Zavolgie have podsol types, which in turn are divided into three subtypes: gley-podsol, typical-podsol, and humic-podsol.

In general, natural conditions in the republic of Middle Zavolgie give ground for intensive forest economy and management. They are also considered favourable for growing forest ecosystems with high biological productivity and ecological stability.

3.4 THE CHARACTERISTICS OF THE RUSSIAN FOREST FUND

The Forest Fund (FF) of the Russian Federation is the aggregation of forest (FL) and nonforest lands (NFL) of a definite administrative unit (forest enterprise, region, republic and country). FL is designated for growing forest and includes Forested Areas (FA) and Unforested Areas (UFA). FA are areas covered by forests with relative stocking rates of 0.4 or more for young stands and relative stocking rates of 0.3 or more for other stands (Forest codex of Russia 1997). UFA are temporarily without forests and include burned areas, dead stands, sparse forests, unregenerated harvesting areas, and grassy glades. NFL include two land types:

- areas that are unacceptable for forest growing under current conditions (mires, rocks, tundra areas, sands, etc.) and
- lands set aside for special purposes (roads, hayfields, etc.).

The Forest Fund of the Russian Federation has been divided into three groups, according to their location and function and the economic and ecological factors involved (Forest Fund 1995).

Group I. The types of forest belonging to the first group include protective forests, which are predominantly used in water-protection and social functions, and forests of extra-conservative territories with very limited industrial harvesting.

Group II. The second group consists of forests in regions with a high population density and a developed traffic infrastructure. These forests have environmental, protective functions and limited economy assignments. In other words, they are mainly protective forests with restricted industrial use.

Group III. The third group consists of territories with a dense cover of forest that is mainly assigned for exploitative functions.

In Middle Zavolgie, 22% (2.5 million ha) of the forest territory belongs to the first group and 44% (5.1 million ha) to the second. The type in the third group covers 34 % (4 million ha) of the forest territory and is found only in the north-eastern part of the Kirov taiga (Figure 5). In the last few years, the area of the forests of the first group has increased (Figure 6). This increase of the first group might be explained by the conversion into this category of some forests of the II and III groups. This has happened as a result of the Russian forest policy aiming at broadening the forest area around cities (green zones), forest shelter belts and the allocation of new regional and national forest parks.

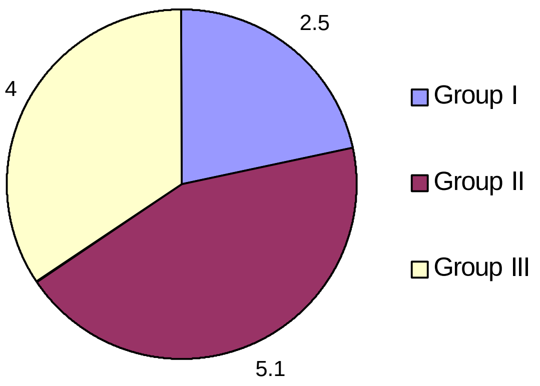

Figure 5. Group of forest in the Middle Zavolgie, mill ha (Forest Fund 1995).

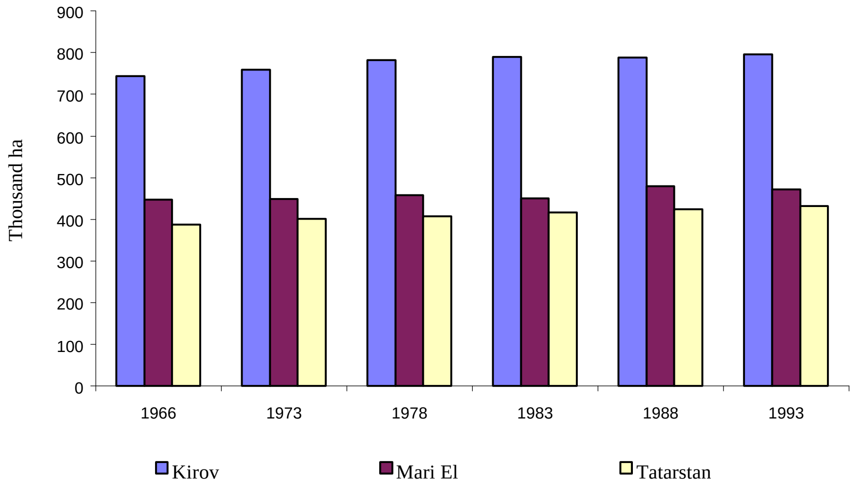

Figure 6. Changes in the area of the first forest group in the Middle Zavolgie (Forest Fund 1995).

According to the constitution and the forest law of the Russian Federation, all forests are owned by the state. To the present, no private forests have existed in Middle Zavolgie (Forest Codex of the Russian Federation 1997).

The forest cover of the territory is very varied. On an average, forests coat 44% of the region. The densest forest cover is found in Kirovskaya oblast with 62% of the area, the second is the Republic of Mari El with 52%. In Nizegorodskaya oblast, forest cover is 46%; and Tatarstan with its 16% has the lowest percentage of forest territory in the region.

3.5 THE MAIN FOREST-FORMING SPECIES

On the territory on the right bank of Volga, the dominant species include pine (*Pinus sylvestris*), birch (*Betula pendula* and *B. pubescens*), spruce (*Picea abies* and *P. abovata*), and aspen (*Populus tremula*). Unlike the other species, oak (*Quercus robur*) is not as widely spread. The proportions of different tree species in the wood stock of Middle Zavolgie can be seen on the attached diagram (Figure 7).

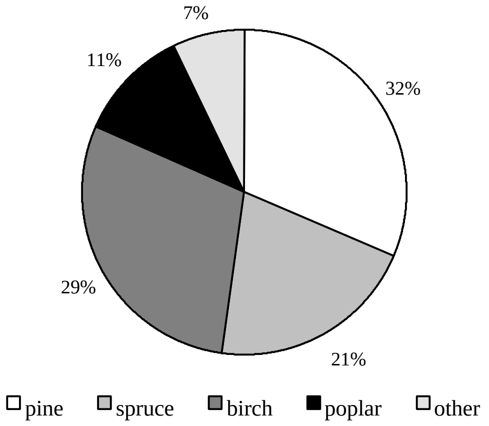

Figure 7. Main species in the Middle Zavolgie, % of the volume (Forest Fund 1995).

The background landscape of the forest ecosystems in the area is dominated by pine stands, which occupy 32 % of the total forest area of 3.2 million hectares. Pine occupies vast territories in Kirov and Nizegorodskaya oblast (Figure 8, 9).

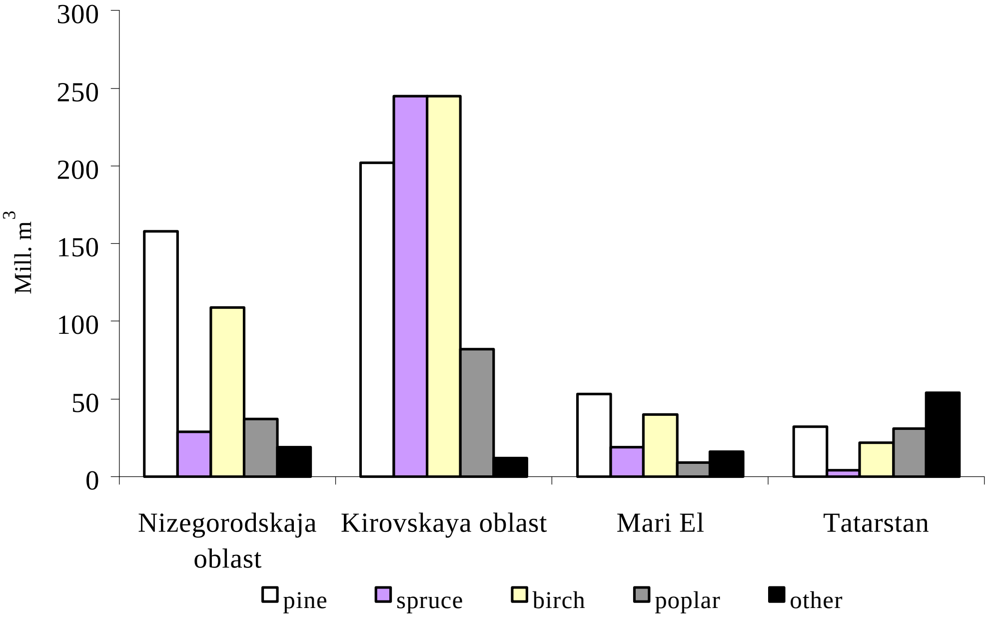

Figure 8. Growing stock wood of main species in Middle Zavolgie (Forest Fund 1995).

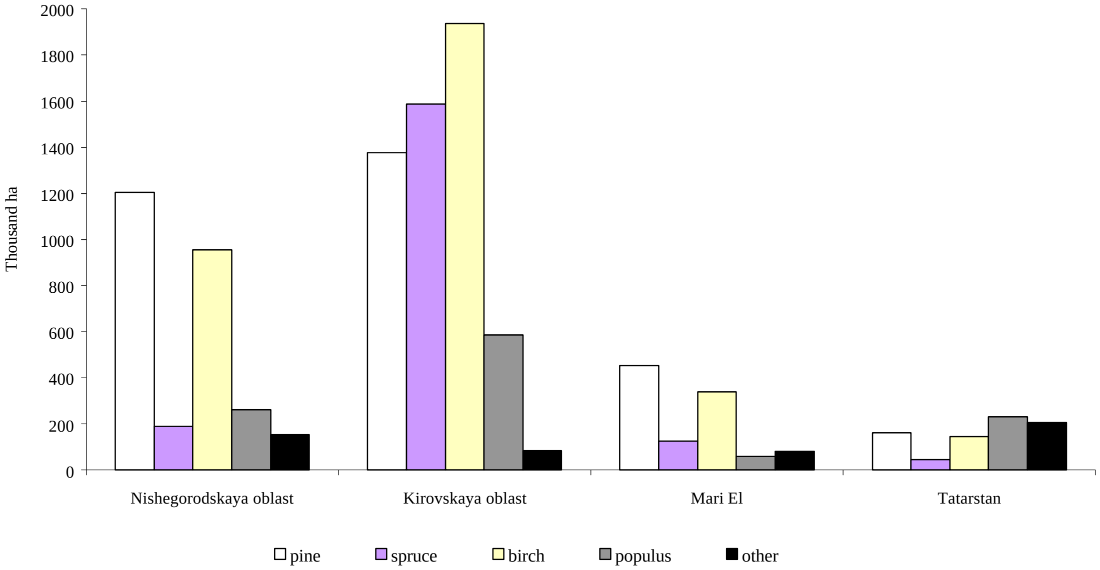

Figure 9. Main species by area in Middle Zavolgie (Forest Fund 1995).

Birch occupies 29% of the whole area, mainly young and middle-aged stands appearing on vast areas recently clearfelled or destroyed by fire. Spruce occupies expansive territories in the north-west and in the northern regions of the area. Aspen is common in mature and young stands. Considerably less spread species include lime, alder, and oak (Figure 10).

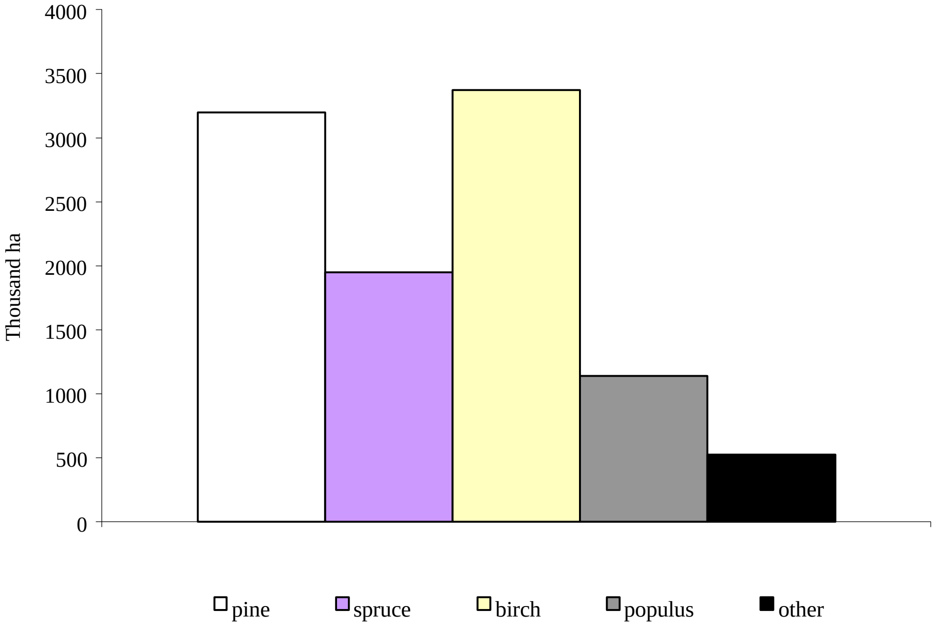

Figure 10. Total area of main species in Middle Zavolgie (Forest Fund 1995).

3.6 THE MAIN SPECIES FOR INVESTIGATIONS

With respect to the annual carbon sequestration, it is possible to specify pine, birch, spruce, and aspen as the main forest forming species in the region. Since Scots pine is an important species for the forestry of Middle Zavolgie, it was chosen as the object of our research.

Pine is generally believed to occupy the largest area and to accumulate the largest amount of biomass. Since it is frost- and drought-resistant and hardy in severe soil-ground conditions, it grows on plains and mountains and forms isle stands in forest-steppe and steppe zones. Its ability to grow in different climatic and soil-ground conditions has contributed much to the formation of pure and mixed stands with spruce and birch, which are very diverse in composition and productivity. Compared to birch, pine is more resistant to the effects of wind. On the territories close to pine forests, the amount of precipitation and air humidity during the vegetation period is higher than in the open steppe, which allows the cultivation of agricultural crops even in dry years.

As is natural for a single species, the fundamental structure of the pine stands is the same over the whole growing area. Needles are in pairs, or sometimes in triplets, and the structure of woody components and the root system is the same. The basic processes, such as photosynthesis and nutrient uptake, are carried out by similar biochemical and tissue structures in all Scots pine trees (Hari et al. 1997).

Pine wood, due to its excellent physical properties and wide distribution, is currently the tree species most used in Russia. It is a species extremely adaptable to varying degrees of the fertility of soil and the availability of water. It is one of the main forest forming species in the forest-steppe and even steppe regions. Unlike the species which are distinct in respect to their high increment of wood and short life period (predominantly of the softwood species), pine stands are characterised by stable growth and high quality, and have good regeneration abilities after harvesting and fires.

Young pine stands grow in most parts of the investigated territory; they cover 47% (1.5 million ha) of all the pine forests of Middle Zavolgie (Table 4). Middle-aged and immature stands occupy 23% and 10% of the area, respectively. The largest area of young pine stands (58%) is in Nizegorodskaya oblast and the Republic of Tatarstan. Middle-aged and immature stands are spread almost evenly all over Middle Zavolgie. Kirovskaya oblast has the largest area of mature and overmature pine stands: 454 000 ha (33% of the whole pine stands area).

Such an age distribution of pine stands is the result of unregulated harvesting of mature forest during the second half of the 19th century. Especially wide clearcuttings have been performed in Middle Zavolgie during World War II and after (Kurbanov and Sokolov 1996).

Table 4. Distribution of pine stands by age groups in Middle Zavolgie, thousand ha (Forest Fund of Russia 1995).

Republic, oblast	Young, 1-40 years	Middle, 41-60 years	Immature, 61-80 years	Mature and overmature, 80 and > years	Total
Nizegorodskaya oblast	699	277	133	96	1205
Kirovskaya oblast	495	303	124	454	1376
Republic Mari El	226	127	45	54	452
Republic Tatarstan	94	38	18	13	163
Sum Total	1514	745	320	617	3196

4. THE PROBLEM OF FOREST AND CLIMATE CHANGE

4.1 LITERATURE REVIEW

The latest publications and research related to forest and climate change may be classified according to the following themes:

- The evaluation of the carbon stock and the annual carbon sequestration in the forest biomass (Kauppi et al. 1992; Isaev et al. 1993; Alekseyev and Birdsey 1994; Isaev et al. 1995; Karjalainen 1996; Shvidenko et al. 1995; Krankina and Harmon 1995; Harmon et al. 1986; Schlamandinger and Marland 1998; Nabuurs and Mohren 1995). Most of the studies concerning the dynamics of the carbon balance have been performed at the stand level (Nabuurs and Mohren 1995; Karjalainen 1996; Usoltcev 1995).

- The prognosis of the changes in the dynamics at different climatic scenarios due to an increasing CO_2 concentration in the atmosphere (Melillo 1993; Zavelskaya 1993; Kondrasheva 1993; Dixon et al. 1994; Cannell 1995; Nilsson and Schopfhauser 1995).

- The determination of the anthropogenic emission of CO_2 and the opportunities of its compensation in the photosynthesis process and carbon sequestration by vegetation (Dudek and Le Blanc 1990; Schroeder and Ladd 1991; Utkin 1995).
- Global carbon cycles in natural ecosystems (Kobak 1988; Dixon and Turner1991; Tarko 1994; Post 1997; Houghton 1998; Schopfhauser 1998). On the continental scale, carbon budget has been estimated for Europe by Kauppi et al. (1992). Some studies with different approaches have been made at a national level. For example, in Russia by Alekseev and Birdsey (1994) and Isaev et al. (1995), in Great Britain by Canell and Milne (1995), and in Finland by Karjalainen and Kellomäki (1996).

- Biological carbon emission into the atmosphere caused by forest fires and forest utilisation (Fosberg et al. 1996; Furyayev 1996).

Of the topics listed above, the first unit is of the most applicable significance in the problem of possible climate change. It is important for the mitigation of possible global warming that the carbon sequestration dynamics are understood and described.

4.2 THE METHODS OF ESTIMATING CARBON IN THE FORESTS OF RUSSIA

Various different methods have been applied to carbon sequestration in Russia. One group of researchers (e.g. Kolchugina et al. 1993) has used various subject maps combined with the database to be differentiated into phytomass fractions of all the vegetation layers of the forest ecosystems (Bazilevich 1993).

Another group of researchers (Isaev et al. 1995, Alekseev and Birdsey 1995) has used results from forest inventory, taking into account whole areas and stocks of wood with respect to the age groups of the main species. With this method, the relationship between the volume stock of the stem and the mass of the tree fractions (wood, bark, branches, roots, and leaves) can be expressed through conversion coefficients, which enable the total phytomass stock per unit area to be calculated. Determination of the carbon has been applied through absolutely dry mass and through the conversion coefficients proposed by Kobak (1988).

Isaev (1995) has, on the basis of an information bank drawn from a number of sample plots, established a conversion coefficient, which enables transferring from biomass to stand volume. He has also deduced average coefficients on the basis of the sample plots, classified by the main species and age classes of the forest stands and the estimated carbon volume in all these areas of forest. He has done this by using received coefficients and information on carbon content in biomass and foliage.

Makarevsky (1991) has used an analogous approach in estimating the amount of organic carbon in the forest and peatlands of Karelia. He reports that the carbon reserve in the forest ecosystems in Karelia is 128.3 MgC/ha, while in the peatland ecosystems it is as much as 1030 MgC/ha. However, he concludes that the net flux of the organic carbon from the forest occurs more to the atmosphere.

Lebkov and Kaplina (1995) have applied their own information bank of forest biomass in transferring from biomass to forest volume by multiple regressive equations of biomass and forest age. In addition, they have managed to calculate the age, when the forest has maximum carbon stock sequestration.

Chertov and Komarov (1997) have elaborated a simulation model (SOMM) for soil organic matter mineralisation, humification and nitrogen release. The model takes into account the rate of the process, which depends on the nitrogen and ash content of litter fall, temperature and moisture. The model reflects the functioning of the main groups of the soil decomposers. The results of the simulation show the applicability of the SOMM to a wide range of environmental areas, from tundra to tropical rain forest.

Another way of determining carbon stocks is also widely recognised, since the calculation is made not only through the area, but also through the volume at the wood stock. Materials of the sample plots, in this way, serve in determining conversion coefficients, allowing transference from the wood stocks to the carbon stocks of the forest ecosystems.

Values of the conversion coefficients for different species allow comparing and matching them with the database of the forest ecosystems. Thus, the following methods of determining phytomass with different levels of approximation to reality may be presented:

a) The calculation of the average value of the conversion coefficient for the different species. By multiplying the said coefficient and the trunk, wood stock obtained during forest assessment, one can determine the value of the phytomass of the forest ecosystem under investigation (Armentano 1980; Birdsey 1992; Kolchugina and Vinson 1993).

b) The calculation of the average statistical conversion coefficient, differentiated in accordance with the species and age groups (Makarevskiy 1991; Isayev et al. 1993; Alexeyev and Birdsey 1994). The value of the phytomass is obtained by means of weighing the average statistical conversion coefficient according to species, forest-covered areas, and stem stock, in accordance with the distribution of the latter in respect to age groups.

c) A more accurate evaluation and estimation of the total phytomass in comparison with the previous ones, because the conversion coefficient is weighed by considering the specific square and stemwood stocks distributed according to two determining factors simultaneously – with respect to age and site (Isaev et al. 1995).

d) At the fourth level of approximation, a sample bank of forest organisation data is classified according to the four determining factors of the forest ecosystem: average age, height, diameter and forest density (Usoltsev 1995). This method is believed to possess a high level of determination and can be applied to the addition of traditional growth and yield tables.
Apart from the conversion coefficients, it can be applied to a wide range of areas, from regression functions to determining phytomass. It should be noted that there are two ways of applying this function, depending on the level of calculation.

While determining the phytomass of fractions of forest ecosystems, an application is made for phytomass dependence on B.A.H (B.A. – basal area, m^2/ha, H – average height of the forest ecosystem, m) or G_{el} (Kurbanov 1994) - elementary stock (G_{el} – phytomass stock in absolutely dry conditions per one m^2 of the basal area of the tree stand). In this case, regression equations have an appearance of conversion coefficients.

The second approach relates to allometry at the level of separate tree taxation. For the tree fractions, phytomass approximation consideration is made of the following taxation indices: tree diameter at the breast height, m (D); tree height, m (H); length and diameter of the crown, m (L_{cr} and D_{cr}). Lately, synergism D^2H has been a common method for representing basal area and height. The introduction of such an index would result in levelling irregularity of model trees sampled from the plants of different types of forest growing conditions. The indices of the crown - $L_{cr \text{ and }}$ D_{cr} are also considered to be of great practical interest. It is typical, in particular, when applying distance methods of evaluation of forest ecosystem bioproductivity.

The productivity of photosynthesis can be determined with respect to chlorophyll index, which is found through the ratio of the assimilated carbon to chlorophyll contents per leaf square and the surface covered with this vegetation. High linear correlation has occurred between the chlorophyll index of the forest ecosystem and the annual sequestration of the atmospheric carbon (Mokronosov 1994). One advantage of this approach might be the possibility of applying distance methods. The drawbacks might include the impossibility of representative data extrapolation on the diversity of forest ecosystems in respect of species composition and mixture character.

Carbon balance investigations on forest ecosystems are mostly concentrated on the evaluation dynamics of phytomass sequestration in forest stands, litter, and soil organic matter (SOM). These processes should be determined with adequate quantitative and time parameters of the carbon cycle in the forest. Therefore, the first part of this study will deal with the dynamics of the carbon sequestration in all components of the pine stands. The second part will be devoted to the assessments of carbon balance at the stand and regional levels.

5. THE ESTIMATION OF THE PINE STAND BIOMASS

5.1 MATERIALS AND METHODS

Sample plots (SP) were established in the normal and modal pine stands of medium to high productivity within a relatively homogeneous area. Most pine stands were selected to represent the full range of stand age groups, tree species composition and a structure typically occurring in these ecosystems. The fieldwork was carried out conforming fully with the Russian forest inventory guidelines (Otraslevoi standart 1983). Materials for the study include also data that has been gathered over different years on sample plots established by the department of forest inventory and taxation of the Mari State Technical University (Kurbanov 1994; Sokolov and Kurbanov 1997; Sokolov and Kurbanov 1999).

Based on the forest inventory data, we determined the distribution of areas with the predominance of *Pinus sylvestris* according to the site classes, basal area and the site class of the forest stands. This became the basis for the investigations regarding two forest types: pinetum cowberry (*Vaccinium vitis-idaea*) and blueberry (*Vaccinium myrtillus*).

Fifteen to twenty trees per sample area were collected for felling. The selection criteria for the sample trees was that the trees should appear healthy, with one main stem, and that their size distribution should be equally represented in the measurements. Mean samples were taken from trees beyond the plot boundaries in proportion to their stem diameter. The crown of each sample tree was cut and divided into three parts: upper, middle and lower. The diameter, weight and length of each branch was measured and divided into sections known as large branches (diameter ≥ 0.8 cm) and small branches (diameter < 0.8 cm). Branches without needles were immediately weighed on scales with a simple comparison made between the weight of the branches with needles and those without them. To determine the moisture of the branches and needles of every part of the crown, three middle-sized model branches were taken.
The sample plots established in pure pinetum cowberry were characterized by density from 0.5 to 1.0. Undergrowth consisting of pine, aspen, spruce and birch is considered to be within sufficient growth.

To investigate pine forest stands, a total amount of 96 sample plots were established and 1426 mean sample trees cut on the territory of republic Mari El and Tatarstan, Nizegorodskaya and Kirovskaya oblast. The sample plots included all the age classes found in the forest stand (Table 5).

Table 5. Main characteristics of the sample plots.

Age, years	Number of plots	Number of sample trees	Mean diameter, cm	Mean height, m	Basal area, m^2	Stem volume, m^3
20 - 28	25	438	6.4 – 13.1	6.3 - 12.8	12.6- 26.4	64 - 146
30 - 45	26	392	11.6 – 16.3	11.4 -17.6	24.6-33.4	138 - 242
56 - 78	24	322	19.9 – 31.6	17.7 - 26.6	33.6 -42.6	263 - 451
82 - 98	15	196	26.4 – 35.2	18.8 - 27.2	34.6- 44.3	320 - 524
104 - 118	6	78	28.4 – 36.8	20.2 - 28.9	36.4- 46.9	330 - 590

For further calculations, we pooled all data from sample plots into a two-class bonitet of normal and modal pine stands. In Russian classification, the potential productivity of a forest ecosystem is characterised by the site class (bonitet) corresponding to Orlov’s scale (Tretiakov 1965). In this classification, site indexes range to seven classes by age and average stand height. The bonitet classes are enumerated with Roman numbers – Ia, I, II, III, IV, V, Va. The highest class (Ia, I) characterises the best-known growth conditions for the forest stand, and the lowest class (V, Va) the poorest one. It should be noted, however, that the bonitet class of the stand is not a characteristic of wood quality. For instance, rotted aspen stand might have I bonitet class (Verkhunov 1986).

Examples of such coniferous productivity estimates for the different ages and all density groups from 0.3 to 1.0 (fully stock stand) in Middle Zavolgie are presented in Table 5. In Russian forest taxation terminology, stand density is the extent of tree density in the ecosystem, characterising the allotment of their anticipation on the occupied area (Forest encyclopedia 1986). There are two kinds of stand density: absolute and relative. Absolute stand density (m^2), or basal area, is a sum of cross sectional squares of all trees on one ha at the breast height. Relative density is evaluated in decimal unit allotment (for instance, 0.9, 0.8, 0.7, 0.6 etc.) for the 1.0 accepted stand density of normal, full stocked forest ecosystem.

For the estimation of the woody detritus on sample plots, each stump, log and snag with a diameter greater than 10 cm and more than 1 m in length was measured (length and diameters at both ends) and the class of decomposition was determined (Krankina and Harmon, 1995). To assess the stages of decay, a four-class system based on physical and structural characteristics was used: decay class 1 of woody detritus is the least decomposed, while decay class 4 is the most decomposed. The species of detritus was determined where it was possible. If a piece of woody detritus had not completely fallen onto the sample plot, measurements were only taken from the part located within the plot borders. Also, the detritus under the forest floor layer was not taken into account. This material was difficult to measure accurately, because of the higher degree of decomposition, although this could be a considerable part of the woody detritus (Little and Ohman 1988).

To determine the decay class and the average density of the wood, detailed studies were made of 3-5 pieces of the woody detritus in each sample plot. In total, 64 dead trees were sampled. First, measurements of the external parameters (diameter, height, and the percentage of bark cover) were made. Next, indicators of decay were recorded, including the presence of rot and wood-destroying fungi. The percentage of the log and snag cover in moss was also estimated, and bark was designated as absent, detached, or sloughing.

Cross-sections were then removed by using a chainsaw to measure the density of the bark and wood. To account for the variation within logs, three to four cross-sections were taken systematically along the length of the bole. The maximum and minimum diameter and height above the root collar of each cross-section were recorded. For each cross-section, the density and the radial thickness of the bark, sapwood, and heartwood, as well as the depth and type of decay were measured. If the cross-section was extremely decayed, the external dimensions were recorded prior to the removal in order to estimate sample volume. From each cross-section, one sample of wood weighing 100-150 g was removed and weighed in the field. In the laboratory, the sample was dried to constant mass at 55^0 and its value proportionally turned to the mass of the entire section to be cut off.

The fieldwork was performed in July and August 1990-1993 and 1995-1999. Sample plots with a minimum of 200 trees in the middle-aged, maturing and mature pine stands and 400 trees in the young pine stands were set up at a distance not less than 30 m from the forest block boundary, trails, roads, and forest edges. The diameter classes were formed by measuring all trees larger than 2 cm diameter at breast height for young and middle aged stands and larger than 16 cm for immature and mature stands. The trees were randomly sampled from three central diameter classes on each plot, five from each class. Diameter at breast height (dbh), bark thickness, tree height, and crown length were measured for each tree of these five classes. Forest floor cover, soil, litter and canopy were also described in detail.

5.2 MOISTURE CONTENT

The moisture content of pine wood varies according to the location of the tree and the time since its cutting. Moisture is found in wood as free water in cell cavities and as absorbed water in the cell wall. The condition in the cell, when the cell cavity contains no free water and the cell wall is saturated with bound water, is known as the fiber saturation point (Husch et al. 1982). It is customary to express the moisture content of wood as a percentage of dry weight. The dry weight of pine crown fractions was calculated by drying a sample of branches and needles at 105^0 C until a stable mass was reached. The percentage of moisture was calculated from:

$$M_c = \frac{W_w - W_d}{W_d}$$

where Mc is the moisture content as a percentage of oven-dry mass, W_w the green mass of wood, and W_d the oven-dry mass of wood.

5.3 REGRESSION ANALYSES

The statistics of dependence were calculated for the regression equations of interdependence between the absolutely dry crown mass and the dendrometry of the stem. The crown mass with the diameter of crown (D_{cr}) and the diameter at breast height (D) has a very high linear positive correlation. For the crown length (l_{cr}), this dependence is thought to be considerable. The dependence of the crown mass with the height (*H*) and the age of trees (*A*) is characterised as moderate (Kurbanov 1994).

During recent years, the index (D^2H) appears to have become very popular among the researchers (Usoltcev 1995; Lebkov and Kaplina 1995; Utkin et al. 1996) as the factor taking into consideration the basal area and the height of the tree. In accordance with this, the connection between the index and the absolutely dry mass has been analysed. The index (D^2H) is generally considered to be rather informative. However, the practical use of this index must be abandoned on account of the difficulties connected with its calculation, since it is easier to use only D or H.

In general, the dependence of the absolutely dry crown mass of the trees on the crown diameter, diameter at breast height and crown length should be used in studying crown of pine trees for the region of Middle Zavolgie. The amount of foliage and branches of trees have often been predicted through allometric equations with breast height diameter as the independent variable (Zagreev 1978, Sokolov 1978, Shugart 1984; Landsberg 1986, Makela A. and Vanninen P. 1998). In this study, we also used allometric relationships between biomass components and diameter at breast height for the modal and normal pine stands.

An analysis of the suitability of the most prevalent regression equations was made in order to determine each component of the crown mass. The selection of these equations was based on the amount of experimental data available, the statistical criteria of equations, and the distribution of residuals. The average age of the sample plots established in Middle Zavolgie was between 20 and 120 years. Therefore, all further analysis and plot fittings were done for this duration.

5.3.1 Needle mass

After analysing the suitability of the equations, it should be said that for determining the fraction of needles of pine crown the most accepted is an S - curve equation, followed by the multiplicative and reciprocal - X equations. Table 6 shows the results of fitting several curvilinear models to the data.

Table 6. Comparison of alternative models for correlation between the needle mass and the diameter at breast height.

Model	Correlation	R^2, %	SE, standard error	F-ratio
S – curve	0.89	79	0.044	1153
Reciprocal -X	0.89	80	0.254	1224
Multiplicative	-0.87	77	0.046	1021
Logarithmic -X	-0.87	76	0.276	988
Double reciprocal	-0.88	77	0.008	1036
Exponential	-0.84	70	0.053	712
Square root- Y	-0.83	69	0.065	685
Linear	-0,82	68	0.321	654

According to the statistics presented in Table 6, the regression S-curve and Reciprocal-X models are very similar. Of the models fitted, the S-curve model yields the highest R^2 value with 79% (Figure 11). This is the selected model. The equation of the fitted model is:

$$N = \exp(1.53 + 4.46/D)$$

Since the P-value is less than 0.01, there is a statistically significant relationship between the needle dry mass (N) and diameter (D) at breast height (at the 99% confidence level). The standard error of the estimate shows the standard deviation of the residuals to be 0.44 (Table 6). The correlation coefficient equals 0.89, indicating a moderately strong relationship between the variables of the fitted model.

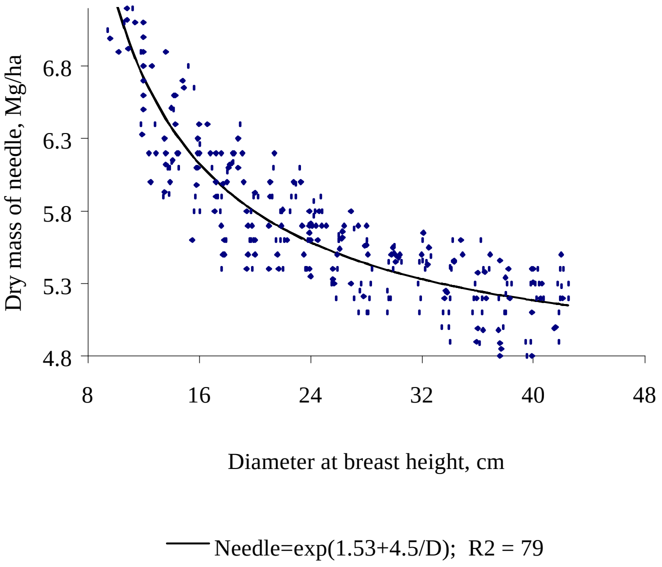

Figure 11. Relationship between needle dry mass and diameter at breast height in pine stands of Middle Zavolgie.

5.3.2 Branch mass

Several curvilinear models of the dependence of the dry mass of pine branches (Br) on the diameter at breast height were fitted (Table 7). A good relationship was found with the Square root-Y, linear and multiplicative equations. Determination coefficients ranged from 84 to 80 and standard errors from 0.371-3.871.

Of the models fitted, the exponential model yields the highest R^2 value with 85 and, therefore, this is the selected model:

$$B_r = \exp(0.32 + 0.08D)$$

The R-squared statistics indicates that the model as fitted explains 82% of the variability in branch mass after having been transformed to a logarithmic scale in order to linearise the model (Figure 12). The correlation coefficient equals 0.92, indicating a relatively strong relationship between the variables. The standard error of the equation shows the standard deviation of the residuals to be 0.322.

We analysed also multiple regression models (equations) for biomass, including a large number of the dendrometry indices in this study. It was determined that the combination of dendrometry indices, such as age, diameter at breast height and crown diameter, are considered to have no essential advantages over the models including only diameter on breast height or crown diameter.

Thus, the equation S-curve for pine needle mass and the exponential model for the branch mass are considered to be the most acceptable for the calculation of the dry crown biomass of pine stands.

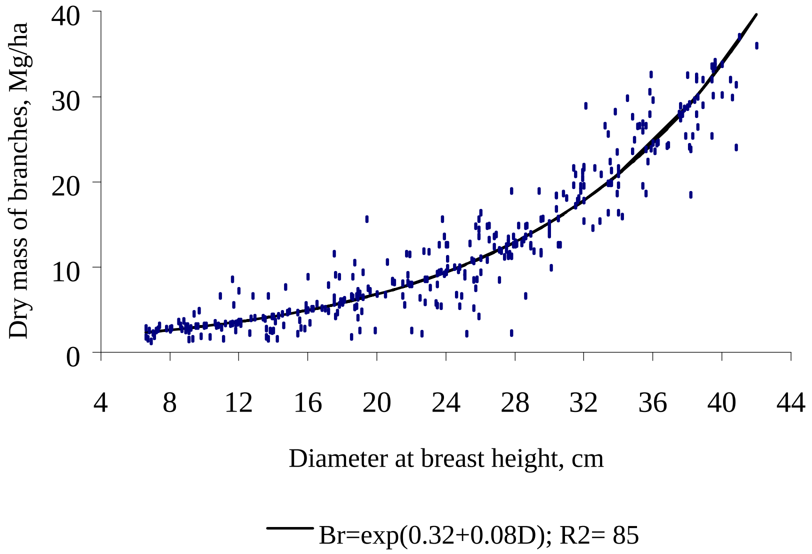

Figure 12. Relationship between branches dry mass and diameter at breast height for the pine stands in Middle Zavolgie.

Table 7. Comparison of alternative models for the correlation between branch mass and diameter at breast height.

Model	Correlation	R^2, %	SE, standard error	F-ratio
Exponential	0.92	85	0.322	1987
Square root-Y	0.91	84	0.473	2279
Linear	0.90	82	3.871	1597
Multiplicative	0.89	80	0.371	1471
Square root-X	0.87	76	4.52	1081
S-curve	-0.82	67	0.481	705
Logarithmic-X	0.82	67	5.229	721
Double reciprocal	0.81	66	0.082	655
Reciprocal-X	-0.70	49	6.583	329

5.3.3 Stem volume

5.3.3.1 Historical overview

Growth and yield tables are considered to provide an inexhaustible source of information for the obtaining of necessary data for forest taxation, numerical correlation dependencies between different taxation indices, determining the maturity of stands, etc. In recent years, growth and yield tables have become models for the carbon sequestration assessment by the biomass of the forest stand.

The growth of forest stands and yield tables have been studied since the very beginning of forest industry. In Russia, the first growth tables have been made in the 1840s by Vargas de Bedemar (Anuchin 1982) by using materials obtained from the sample plots of the former Tulskaya (oak) and St. Petersburg (pine and spruce) provinces. In the 20th century, a great deal of research has been devoted to growth tables. In particular, tables of this type have been made for pine forest stands Dobrovliansky in 1909 for the Kiev province and Turin in 1913 for Arkhangelsk province (Turin 1931).

In subsequent years, Tretiakov et al. (1965), Shustov (1940), and Milovanovitch (1937) have made significant contributions to table creation and development. Since then, many writers have addressed this issue. Among the most significant works are investigations made by Antanaitis (1969), Gorsky (1962), Moshkalev (1990), Svalov (1979), Zagreev (1978), Sokolov (1978), and Verkhunov et al. (1991).

The above list of writers is not complete. Many of them have continued their studies on forest stand growth through the application of new approaches and modelling functions of growth.

Currently, a large number of forest stand growth simulations exist. For example, Svalov (1979) has given 13 functions applied to the modelling of forest stand growth in height (H, meter), the first of which dates back to 1878. He has summarised the results of the analysis of the greater part of the functions given by other writers and has investigated the three most appropriate functions, namely:

Korsun (1935)
$H = t^2/(a+bt+ct^2)$;

Drakin and Vuevsky (1940)
$H = a\,(1- e^{-kt})^m$;

Korsun, Asmann and Frantz (1964)
$Lg_H = a + b\ln t + c\lg^2 t$,

where *H* is height; *t* is age; *a, b, c, k, m* are growth parameters; the biological meaning of which is not given by the writers.

The principal criteria taken into consideration here are the accuracy of the experimental data for all ages of the forest stand; the suitability of the functions offered for extrapolation beyond the age limits (making selections from the sample plots) and the convenience of their application.

A researcher at the Voronezh Forest Engineering Institute, Gutman (1986), has proposed his own variant of the model of growth for forest stands and its practical application for the fitting of taxation indices. Differential equations regarding the dynamics of the stands stock have been the basis for the model:

$d_v = l(t)dt/y - d_w$,

where *dv* is the increment of the stand biomass for the time *dt* on the unit square of the stand; *dw* is the biomass consumed by the stand on the unit area of the stand for the time *dt*, required for providing its vital functions; *l(t)* is the physiological radiation absorbed by the stands for the time *dt*; *y* is the gross production of the stand - the amount of light energy necessary for the production of the unit of the biomass produced.

For modelling the tree growth with respect to height and diameter at breast height, Moshkalev (1990) suggests that the following equation should be used:

$y = a_0(1\text{-}e^{A\ a1})^{a2}$,

where *y* is the index modelled; *A* is age (years), *a0 ...a2* are kinetic coefficients, of which the numerical values are obtained according to the results of annual ring count on specified stem cuts. To determine the model coefficients, the least square method in connection with the iteration one is used.

Yuditzky (1982) has offered a new mathematical growth function:

$y= a_1F_ì(a_2t + a_3)+a_4$,

where *y* is the taxation feature under investigation, *t* is age, a_1, a_2, a_3, a_4 are function parameters, and $F_ì$ is Markov’s function (that differs from the Gauss-Laplace function, because of its lower limit of integration and the numerical coefficient).

A new growth function offered by Yuditzky (1982) is different, due to its universal approach. It allows the application of a common (unified) formula for all site classes, achieved by applying the parameters of a_1 and a_4.

5.3.3.2 Estimating the stem volume with Mitscherlich s function

It is common knowledge that the selection of sample plots, when taking into consideration the natural process of forest stand development in nature, is determined by various objective conditions. The most significant of these conditions include the biological peculiarities of different tree species, the characteristics of their competition with other species, climate conditions and stand density. All these considerations make it difficult to select a sample plot covering certain life stages of a forest stand. Taking the above into account, we did not set the task of making growth table sketches, as it is commonly understood, i.e., finding the dynamics of taxation indices and showing the lines of development of forest stands.

The purpose of this investigation is, however, to determine the most feasible values of the taxation indices, depending on the site class. The investigation of forest stands and their natural development is not the main purpose, but, rather, to obtain taxation table index values in stages, i.e., by taking age into account. The starting point of this investigation has been to use taxation indices as the basis of valuation and inventory of the forest fund: mean height and diameter, basal area and standing volume (Table 5).

In this study, the concept of stem volume includes all the wood and bark above the highest root collar that hampers cutting. If there was no root collar to interfere with bucking, the calculation of stem volume was begun 5 cm above the ground.

The volume of each test tree was calculated from the diameter data on different relative heights, and tree height with the help of linear regression analyses.

Mitscherlich's function was used for pine stand growth calculation in Middle Zavolgie (Chernikh 1992). This function satisfactorily describes the general regularities of the growth of living organisms:

$$T = T_{max}\,[1-e^{(-A*C1)}]^{C2},$$

where *T* is modelling taxation index as a function of diameter (cm), height (m), sum of cross-sections squares (m^2), stock (m^3); T_{max} is asymptotically the value of the taxation index for a given natural forest stand development; *A* is age, years; *e* is the base of the natural logarithm; *C1* is growth parameter; *C2* is the parameter of curve form.

Mitscherlich's growth function is considered to be non-linear as far as its parameters. To find optimal numerical values for the parameters *C1* and *C2*, the following iteration method was used:

1. In the model, for each point (with respect to age) of the natural stand, the taxation indices *C1* were calculated, as the values of *C2* (1,2,3,4...10) were fixed according to the formula below:

$$C1_1 = \frac{Ln(1 - Top(A)/T_{max})^{1/C2}}{A}$$

where *Top(A)* is the actual value of the taxation index in the age *A*; *i* is 1,2,3,4.....n; and *n* is the number of observations.

2. Taking into account the least function error, the parameter *C2* was set as constant.

3. At the constant value of the parameter *C2,* the smoothing of the parameter *C1* was made for all points of the natural stand, according to the polynomial of the 3rd degree.

4. The parameter *C2* was estimated according to the equation below:

$$C2 = \frac{Ln(Top(A)/T_{max}}{Ln(1 - e^{-A*C1'})}$$

where *C1'* is the estimated values of the parameter *C1*, according to the polynomial of the 3rd degree.

5. The parameter C2 smoothed according to the polynomial of the 3rd degree.

This algorithm was used as the basis for modelling the dynamics of the taxation indices such as the mean diameter and height, basal area and the stem volume for the pine forest ecosystem (Table 8).

Table 8. Taxation index dynamics for normal pine stands in the region of Middle Zavolgie, hectare level averages.

Age, years	Mean Height, m	Mean DBH, cm	Basal area, m^2	Stem volume, m^3
I site class				
20	11.0	10.6	23.1	49
30	12.0	12.6	27.2	135
40	15.9	14.5	30.1	216
50	19.1	19.5	35.4	293
60	21.6	24.0	38.9	361
70	23.6	27.9	41.2	419
80	25.2	30.9	42.7	468
90	26.6	33.3	43.8	508
100	27.8	35.1	44.6	541
110	28.8	36.5	45.3	567
120	29.8	37.5	46.0	589
II site class				
20	8.7	9.1	18.6	42
30	10.0	10.7	21.2	105
40	13.9	11.7	27.5	174
50	16.6	14.8	32.9	236
60	18.2	17.8	36.5	296
70	19.5	20.7	39.0	353
80	20.7	23.5	40.7	404
90	22.4	26.3	42.1	449
100	24.6	28.7	43.4	486
110	26.9	30.6	44.5	516
120	28.7	31.9	45.2	538

When carrying out forest assessment in the region of Middle Zavolgie, normal yield and growth tables for pine stands are usually used. As a result of harvesting, these tables, however, do not sometimes represent adequate taxation data. Therefore, the most complete and correct picture of taxation index growth dynamics can be given by the modal forest stands as the most widespread at present (Table 9).

5.3.3.3 Comparison simulated data with other references

Newly obtained taxation index values for normal stands were compared to the data presented by a number of other writers. This data is currently used as reference literature for forest regulation and is also used in forest companies.

Table 9. Taxation index dynamics for modal forest stands of the region of Middle Zavolgie.

Age, years	Mean height, m	Mean DBH, cm	Basal area, m^2	Stem volume,m^3
I site class				
20	10.6	10.2	7.8	39
30	11.8	11.9	8.9	81
40	15.7	16.1	11.7	149
50	18.3	20.0	15.1	217
60	20.6	24.2	18.3	278
70	22.6	27.9	21.0	327
80	24.4	31.3	25.7	364
90	26.1	34.4	28.1	390
100	27.9	37.0	31.1	406
110	29.4	39.2	33.6	416
120	31.0	40.9	34.8	425
II site class				
20	8.4	7.3	7.2	35
30	9.6	9.4	8.3	71
40	13.3	12.6	12.0	132
50	16.2	15.9	14.8	195
60	18.4	19.3	17.2	251
70	20.1	22.8	19.9	296
80	21.6	26.2	23.0	330
90	23.0	29.5	24.9	353
100	24.4	32.5	26.7	366
110	25.8	35.2	28.4	379
120	27.1	37.3	31.6	395

As can be seen in Table 10, the largest deviation of our data, in respect to the mean heights for the first site class, is observed from the mean heights given by Vargas de Bedemar (1840) for the pine stands of the region of Leningrad. It is considered especially characteristic of the age group from 30 to 50 years, where the deviation ranges from -11% to -12%. Minimum deviations have occurred in the data presented by Verkhunov (1991) for normal pine stands in the plain part of the Perm oblast. In the second site class, the largest deviation (+13.0) of mean heights is observed in the data of Turin (1956) for 80-year-old pine stands.

The newly obtained tables for the modal pine stands are noticeably different from the normal stands in respect to volume and basal area. This difference may be related to the fact that practically all the modal stands have been subject to a number of different cutting operations.

The approximation of the taxation index dynamics for pine stands has produced good results with the help of the Mitscherlikh function. This has been especially true while fitting the stem volume, diameters and heights. The only drawback has been the fact that the function has asymptote parallel to the age axis and, therefore, is considered to be strictly increasing. Therefore, its application is limited by the age of natural maturity, when growth decreases.

Table 10. The dynamics of the newly measured mean heights for normal pine stands in the region of Middle Zavolgie, in comparison with data compiled by other writers.

Age, years	Measured height, M	Deviation from data, %				
		V	T	VN	VB	M
I site class						
30	12.0	-	+ 2.5	+ 5.8	- 10.8	+ 7.6
40	15.9	+ 0.6	+ 1.9	+ 3.1	- 11.9	+ 2.5
50	19.1	- 0.5	+ 2.6	+ 2.6	- 10.5	+ 0.5
60	21.6	- 0.5	+ 3.7	+ 2.8	- 3.7	+ 0.9
70	23.6	0	+ 5.1	+ 3.4	- 7.2	+ 2.1
80	25.2	+ 1.2	+ 6.0	+ 4.O	- 5.6	+ 3.6
90	26.6	+ 1.9	+ 6.8	+ 3.8	- 4.9	+ 4.5
100	27.8	+ 2.5	+ 7.6	+ 3.6	- 3.6	+ 5.0
110	28.8	+ 3.1	+ 4.2	+ 3.5	- 2.8	+6.9
120	29.8	+ 3.0	+ 7.4	+ 3.0	- 2.7	+7.4
II site class						
30	10.0	-	+ 6	+ 4.0	- 9.0	+ 10.0
40	13.9	- 2.2	+ 0.7	- 2.2	- 14.4	+ 1.4
50	16.6	+ 3.0	+ 2.4	- 1.2	- 12.0	+ 6.0
60	18.2	+ 1.1	+ 7.1	+ 3.3	- 6.0	+ 4.4
70	19.5	+ 4.6	+ 11.3	+ 6.7	- 1.5	+ 7.2
80	20.7	+ 6.8	+ 13.0	+ 6.8	+ 1.4	+ 9.7
90	22.4	+ 4.9	+ 11.2	+ 6.3	+ 0.9	+ 8.0
100	24.6	+ 0.5	+ 6.5	+ 1.6	- 2.0	+ 4.1
110	25.8	- 0.4	+ 5.4	+ 0.4	- 1.9	+ 4.3
120	27.1	- 2.2	+ 3.3	- 1.5	- 4.1	+ 3.3

V Verkhunov, P.M. 1991 (growth of normal pine stands for the Perm oblast);
T Turin, A.V. 1956 (the growth of predominant pine stands of the USSR; general tables);
VN - VNIILM 1956 (growth of normal pine stands of the USSR);
VB - Vargas de Bedemar 1840 (growth of predominant pine stands for the Leningrad oblast) ;
M Moiseenko, F.P. 1990 (growth of pine stands for the Arkhangelskaya oblast).

These tables of the taxation index dynamics for normal and modal pine stands can be recommended for application in forest inventory in the region of Middle Zavolgie. The comparison of the tables with the field data from different parts of Middle Zavolgie gave rather satisfactory results.

For further carbon assessments, the determined stem volumes (V_{st}, m^3) for normal and modal pine stands were converted to biomass components (M_{st}, Mg) by the biomass ratio (R_b, Mg/m^3):
$M_{st} = V_{st} \cdot R_b$ (Kellomäki et al. 1992)

The biomass ratio (wood density) varies substantially in relation to the quality of the site, the position of the tree, and the age and section of the stem. In young trees and on fertile sites, wood density is lower than in mature trees and on poor sites; i.e. the fast growth rate of Scots pine indicates lower wood density than slower growth rate (Kellomäki et al. 1992). The overall mean density of 381 kg/m^3 for Scots pine was applied to our calculations.

5.3.4 The calculations of the understorey

The understorey of pine forests includes forest floor vegetation, undergrowth and shrubs. The data of the sample plots shows very considerable variability in this layer in pine forests. The mass of understorey is low in young and middle-aged pine stands. With the ageing of the stand and natural mortality, the biomass of the bottom layer increases.

In the pine forests of Middle Zavolgie, the undergrowth consists of spruce (*Picea abies*), birch (*Betula pendula*), aspen (*Populus tremula*), and oak (*Quercus robur*), and the shrubs include alder buckthorn (*Frangula alnus*), juniper (*Juniperus communis*), filbert (*Corylus avellana*) and *Euonymus verrucosa*.

The forest floor vegetation consists of *Vaccinium vitis-idaea*, *Vaccinium myrtillus*, *Calamagrostis arundinacea*, *Geranium sylvaticum*, *Vicia sylvatica*, *Majanthemum bifolium*, *Hieracium umbellatum*, *Bryophyta*, *Fragaria vesca*, *Lucopodium clavatum* and *Antennaria dioica*, each being typical of different stages in stand development.

Undergrowth and shrubs have a significant effect on the forming of the floor vegetation. The alteration of the undergrowth biomass by three times changed the biomass of the forest floor four times (Saevich 1986).

In order to examine the relationship between the understorey and site conditions and stand age, we simulated understorey dynamics based on different analyses by using data from the sample plots. The undergrowth, shrubs and forest floor for the first site of modal pine stands have different type of best-fit curvilinear models to the sample plot data (Table 11).

Table 11. Fitting models for different components of the understorey in pine modal stands on the I site class.

Understorey Components	Model	Correlation	R^2, %	F-ratio	Standard Error
Undergrowth	Square root-Y	0.97	96	179.6	3.12
Shrubs	Multiplicative	0.98	96	206.02	0.31
Forest floor	S-curve	-0.97	95	175.28	0.12

For the undergrowth, the best fit was with square root-Y regression equation:

$Un = (a + b \cdot A)^2$,

where Un is the dry mass of the undergrowth, a = 3.47, b = 0.42, A age.

Since the P-value is less than 0.01, there is a statistically significant relationship between the undergrowth and stand age (99% confidence level).

The biomass of shrubs has been best smoothed by a multiplicative model:

$Sh = a*A^b$,

where Sh is the dry biomass of the shrubs, a = 0.01, b = 2.45.

The biomass of the shrubs has relatively stable growth of the main stand age, up to 40 years. Between 40 and 120 years, the mass of the shrubs develops quickly.

The biomass of forest floor for the I site class of pine modal stands has been best described by the S-curve model:

$Fl = \exp(a + b/A)$,

where Fl is the dry mass of the forest floor, $a = 8.79$, $b = -38.76$.

The R^2 statistic indicates that the model, as fitted, explains 95% of the variability in the forest vegetation floor biomass, after having been transformed to a logarithmic scale to linearize the model. The forest floor increases with the ageing of the forest, up to 80-90 years. After this, the open forest canopy allows too much light on the forest floor, and its growth stabilises.

The best fitted models for the understorey components of modal and normal pine ecosystems have been given afterwards.

Models for the understorey of the II site class modal pine stands are:

$Un = (0.70 + 0.42*A)^2$

$Bu = \exp(2.25 + 0.04*A)$

$Fl = \exp(8.56 - 26.37/A)$

Regression equations for the normal pine stand are:

I site

$Un = 1/(-0.0006 + 0.084/A)$

$Sh = 2.304 + A^{1.375}$

$Fl = \exp(9.27 - 71.19/A)$

II site

$Un = (3.34 + 0.48*A)^2$

$Sh = 2.22*A^{1.35}$

$Fl = \exp(9.27 - 7/A)$

5.3.5 Soil organic matter

While carbon is partly accumulated in the above- and belowground biomass in pine forests, a considerable pool exists also in the forest soil. Soil organic carbon is a long-term stock compartment for the atmospheric C. The size of the soil C pool is significant, and the changes in this pool are relatively slow, unless it is disturbed (Jenny 1980; Schlesinger 1990).

Soil organic matter originates from the above- and belowground litter that is produced by autotrophic plants and microbes, exudates leached from plant roots and soluble organic compounds in throughfall. Thus, a substantial amount of carbon, which has been bound in photosynthesis, is transported to the soil.

Boreal forests are characterised by a thick organic layer, a large stock of carbon and a slow rate of decomposition process. Changes in the atmospheric CO_2 concentration, temperature, precipitation and nitrogen input will have many direct and indirect effects on the carbon pools of forest soils. Rastetter et al. (1991) and Melillo et al. (1993) have shown that the long-term responses of the forest ecosystem to the changing environment will be dominated by changes in soil processes.

Pine forests of Middle Zavolgie grow mainly on podzol and humic-podzol soils (Kurbanov et al, 1994). A very acid humus layer characterises those soils. Sandy podzol soils generally have the following structure of vertical profile: AO- AO''- AOA1 - A2 - Bhf - C_m -D.

Level AO-AO'' has a rather thick (13-15 cm) forest floor with two or three layers, tree roots and fungus passing through it. This layer changes over to AOA1 (1-2 cm) humus-mineral horizon.

The next layer, A2, has a strongly marked unstructured podzol horizon with the thickness of 30-35 cm. The podzol horizon transfers to brown colour Bhf alluvial-humus-iron level (to 20 cm), which accumulates alluvial humus and iron. The humus has low content in podzol horizon (0.1-0.4%), and it increases noticeably in the alluvial horizon Bhf (to 2.5%). C_m is matrix soil, D - bottom (Forest encyclopaedia 1986).

The carbon content in the mineral part (without forest litter) of podzol soils (0 - 100 cm) was investigated in collaboration with the department of forest soils of the Mari State Technical University, and further calculations are based on the results of earlier work (Kurbanov et al. 1994).

5.3.6 Belowground biomass in the pine stand

The information available on above-ground biomass and its dynamics is many times greater than that for root biomass. Investigation of the belowground biomass is difficult. Therefore, the pine roots on the sample plots were not studied.

Coarse root dynamics are largely determined by above-ground biomass dynamics (Kurz 1989; Vogt et al. 1991). The biomass of roots was calculated with the help of Shvidenko et al. (1996) equation developed for the European part of Russia:

$$R_{v(bl)} = (a_0 + a_1 \cdot A + a_2 \cdot A^2) \cdot A^{a3} \cdot V^{a4} ,$$

where $R_{v(bl)}$ is belowground forest stand biomass (Mg of dry matter for each cubic meter of growing stock), A is the average age of a stand in years, V growing stemwood stock in m^3, and a_0, a_1, a_2, a_3 and a_4 are regression coefficients.

Since this allocation equation does not consider fine roots, it can be assumed that fine roots have about one third of the mass of foliage (Vanninen et al. 1996). Determined dynamics of belowground biomass for modal and normal pine stands are presented in Figure 13.

5.3.7. Biomass of detritus

In the recent studies of carbon cycling in Russian forest ecosystems, the main focus has been on the biomass of live plants, carbon stores in soils and in peat, while the role of carbon stored in woody detritus (WD) has been practically ignored (Utkin 1995; Isajev et al. 1995). That might have been connected with the fact that during the Soviet period the priority in forest science was given to the studies of forest as a raw material. Great attention was paid to forest stand composition, growth dynamics, merchandise and assortment structure and other technical characteristics of the wood. In other words, everything that could be used in the developing industrial production and construction was studied. Therefore, the studies of the woody detritus in the forests of Russia during the Soviet period were rather limited.

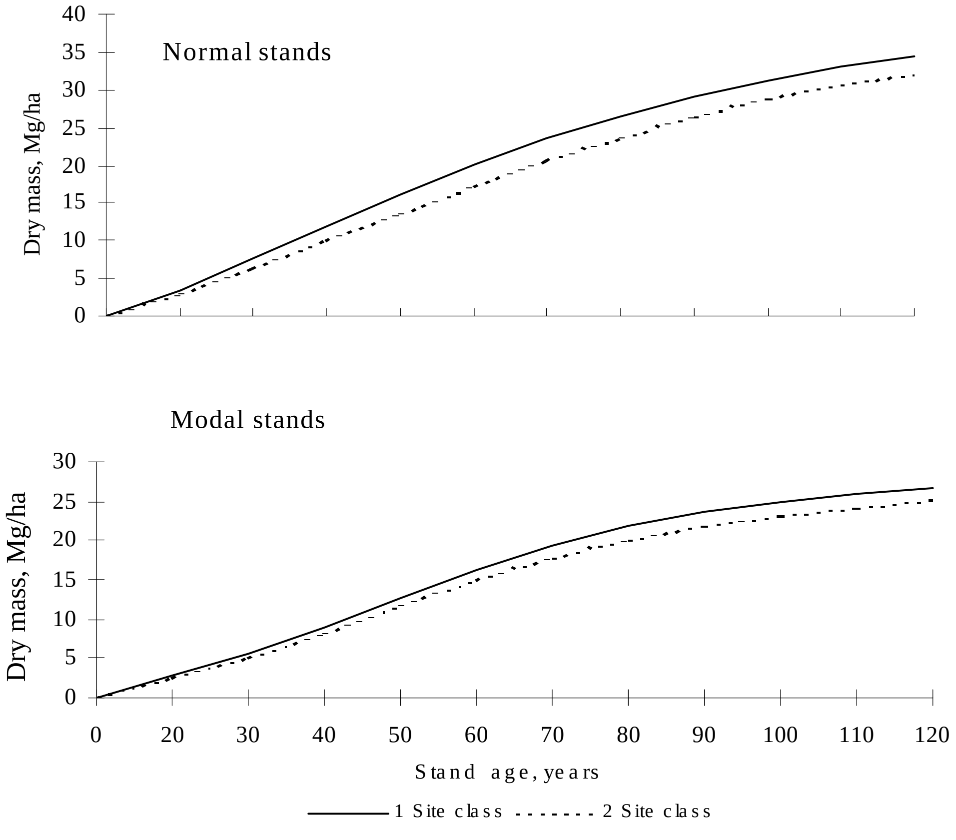

Figure 13. Dynamics of belowground biomass in the pine stands in Middle Zavolgie.

In Russian forest mensuration, it is common to determine woody detritus by means of growth and yield tables, by using the column that shows the growing stock of trees “retarded in growth”. According to a definition (Anuchin 1982), this category includes trees that are relatively weak, ill, damaged by insects, and that should be thinned out in due time. However, in the commonly used growth and yield tables, the processes of tree mortality and woody detritus decomposition are not taken into account. The accumulated totals of trees “retarded in growth” are likely to provide an erroneous estimate of the accumulated store of dead wood. This is especially true in older pine stands, where a certain part of the dead wood is removed from the stands during commercial cuttings.

In studies on biological carbon turnover, woody detritus is often viewed as something intermediate between the live biomass of the growing forests and soil organic matter. In particular, in the forest carbon cycle, it is considered to perform an intermediate function of the carbon sequestration by storing the carbon accumulated in the stand growth process, and gradually turning it into soil organic matter. As a result of the relatively large size and low nutrient concentrations of the detritus, it decomposes more slowly than fine litter and takes decades to turn into forest soil (Harmon et al. 1986; Fahey et al. 1999; Brown et al. 1996).

The lifetime of the carbon contained in the woody biomass of forest stands is expected to be long. For example, a mature Douglas fir tree is dead wood approximately half of the time it is in an ecosystem (Drengson and Taylor 1997). If decomposition rates are slower than rates of biomass accumulation of replacement trees, the forest becomes a carbon sink, which may be of consequence when extrapolating large forest areas (Lugo and Brown 1992).

Another potentially significant role of the woody detritus in the Middle Zavolgie region of Russia might be its providing important habitat elements for a wide array of biota and its maintaining a biodiversity of organisms associated with the decomposer food chain in pine forests (Brown et al. 1996, Goodburn and Lorimer 1998; Drengson and Taylor 1997).

In many economically developed countries of the world, studies of dead wood are not conducted. This is because intensive forest management in these countries harvests and utilises nearly all the woody biomass produced by forests and leaves very little woody detritus. This cannot, however, be said about the forest sector of Russia, where low-intensity forest management causes a large flow of material into woody detritus pools.

Woody detritus in the form of logs, snags, stumps and branches develops as a result of tree mortality during stand development and growth. In addition, woody detritus is produced during timber harvest, including clear-cutting, sanitary cuttings and thinnings, during which a large proportion of woody biomass is left in the forest to decompose.

Measurements of woody detritus in the north-western Russia showed that dead wood stores are highly variable and largely controlled by disturbance and management practices (Krankina and Harmon 1994). The share of dead wood in the total above-ground organic matter ranged from 2 to 98%, depending on the disturbance regime in the region. This suggests that the use of a single live/dead wood ratio across the range of successive stages, which is a common practice in carbon budget calculations, may substantially over or underestimate the dead wood carbon pool (Krankina and Harmon 1995).

Evaluating woody detritus is especially important for the forests of Middle Zavolgie. In the mid-20th century, large areas of forests in the region were disturbed by fires, clearcutting, damages of the World War II and insect outbreaks (*Melolontha*) during the 1970s. The combination of these disturbances has caused an increase in the regional store of woody detritus, but the actual amounts involved have never been measured.

The biomass of the woody detritus was calculated by multiplying the volume of woody detritus by the average density of the material in each of the four decay classes. Woody detritus was inventoried in 4 decomposition classes and the density of dead wood in each class was established by using destructive sampling (Krankina and Harmon 1995, Kurbanov and Krankina 2000). To determine the decay class and the average density of the wood, detailed studies were made of 3-5 pieces of the woody detritus in each sample plot. The total of 64 dead trees was sampled.

The initial density of the samples was calculated as the ratio of the detritus dry mass to green volume. After this, density values were averaged to each decay class (Table 12). To simplify calculations of carbon content in the woody detritus, wood density was converted into MgC/m^3 based on 51% carbon content (Sollins et al. 1987).

Table 12. Decay class system for woody detritus in the pine forests of Western Russia.

Decay class	Number of samples	Density mean and SE, (MgC/m^3)
1	28	0.245±0.053
2	26	0.196±0.049
3	24	0.131±0.068
4	15	0.084±0.098

Next, the volume of each type of dead wood (snags, logs, stumps) was estimated by using volume tables (Tretyakov et al. 1952). The average values of the decay classes were used to convert the measured volume of woody detritus into carbon stores.

Variation in the detritus biomass over time may also be caused by episodic mortality factors. For instance, wind throw or insect attack, for example, from bark beetles, can result in an abrupt and large input of woody detritus. Thus, stands of most ages can have high amounts of detritus when mortality is high, whereas other stands tend to have very limited amounts of woody detritus, if no major mortality has occurred for a long time (Clark et al. 1998). In addition, stand history, including differences in fire behaviour and fire intensity, may help to explain large variability in woody detritus biomass within a forest type (Agree and Huff 1987).

Therefore, except for age, we refrain from establishing a specific relationship between the stores of woody detritus and the tree parameters of the forest stand.

Table 13 shows the results of fitting different models to describe the relationship between woody detritus and age of the pine stand. The best equation of the fitted models is multiplicative:

$Wd = 0.007*A^{1.6}$ (for modal pine stands),
$Wd = 0.008 *A^{1.6}$ (for normal pine stands),

where Wd is woody detritus, and A is the age of the pine stand.

The R^2 statistic indicates that the model, after having been transformed to a logarithmic scale to linearise it, explains 87% of the detritus variability. The correlation coefficient equals 0.93, indicating a relatively strong relationship between the variables (Figure 14). The standard error of the estimate shows the standard deviation of the residuals to be 0.354.

Table 13. Comparison of alternative models for the correlation between woody detritus mass and the age of the pine stand.

Model	Correlation	R^2, %	SE, standard error	F-ratio
Multiplicative	0.93	87	0.353	337
Square root-Y	0.93	87	0.422	362
Exponential	0.91	84	0.391	266
Linear	0.91	82	2.942	247
S-curve	-0.90	82	0.413	234
Square root-X	0.88	78	3.311	185
Double reciprocal	0.85	72	0.181	133
Logarithmic-X	0.85	72	3.765	131
Reciprocal-X	-0.75	56	4.701	65

5.3.8 The results of the calculations

Several linear and non-linear models were applied to direct and log-transformed data. Because the errors associated with the final equations will be disseminated in our further computations, the main emphasis in choosing the model was given to the highest R^2 and smaller standard error based on normally distributed residuals that had no bias or evident trends. Although such data as height, age, diameter at breast height, crown diameter and the basal area of the stand were available for the simulation, initial analysis has shown that only diameter and the age of the stand are useful in predicting the different fractions in pine ecosystem.

Mitscherlich’s growth function gave good results in the simulation of stem mass (Figure 15). The bark of the stem in both site classes had the maximum value in 80-90 years of age and a slight decrease after 90 years of age (Figure 15). Total crown mass increased up to 100 years. Branch mass reached the maximum at 100-120 years. Needle mass was at the maximum at 20-30 years with a stable decrease up to 120 years (Figure 16).

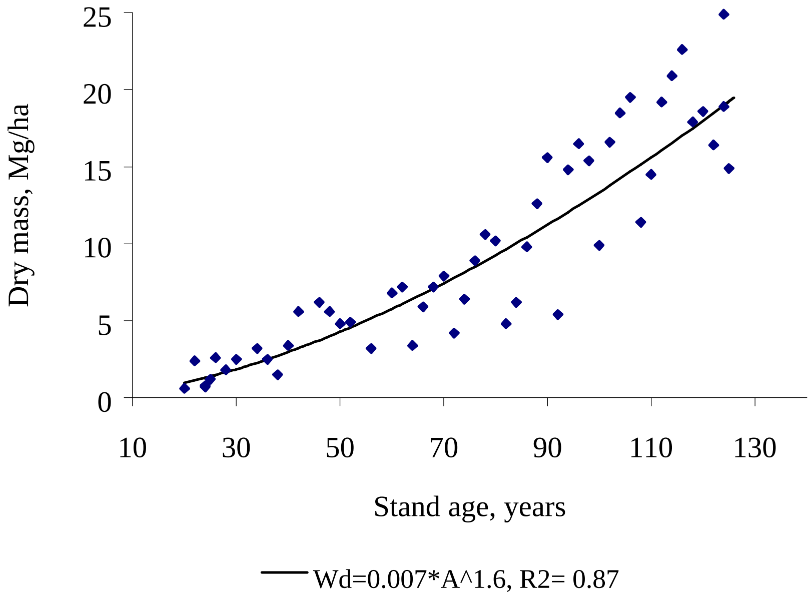

Figure 14. Relationship between woody detritus and stand age in the modal pine stands of Middle Zavolgie.

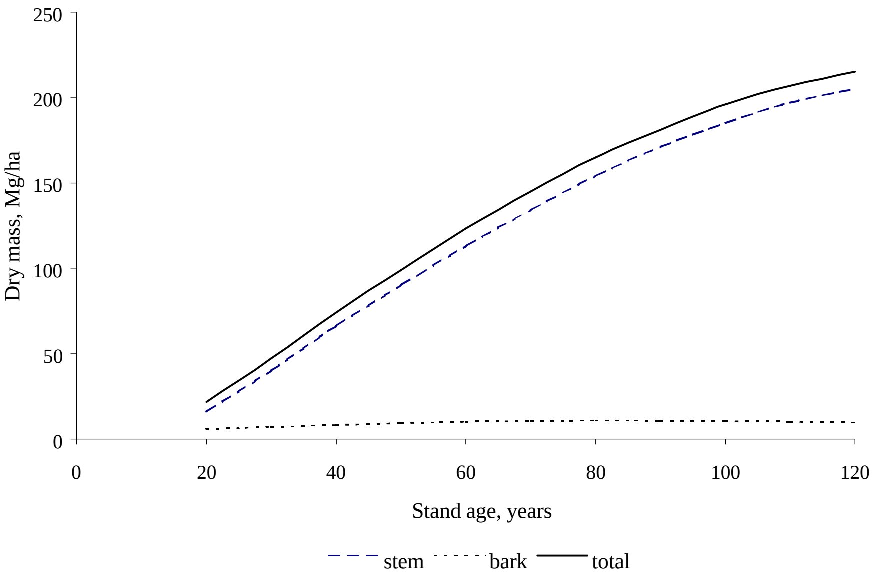

Figure 15. Dynamics of the stem mass for the II site class of normal pine stands in Middle Zavolgie.

Fraction of needles, branches, stem, undergrowth and woody detritus were positively correlated with diameter on breast height and age of the pine stand (R^2=78-96% at the 99% confidence level).

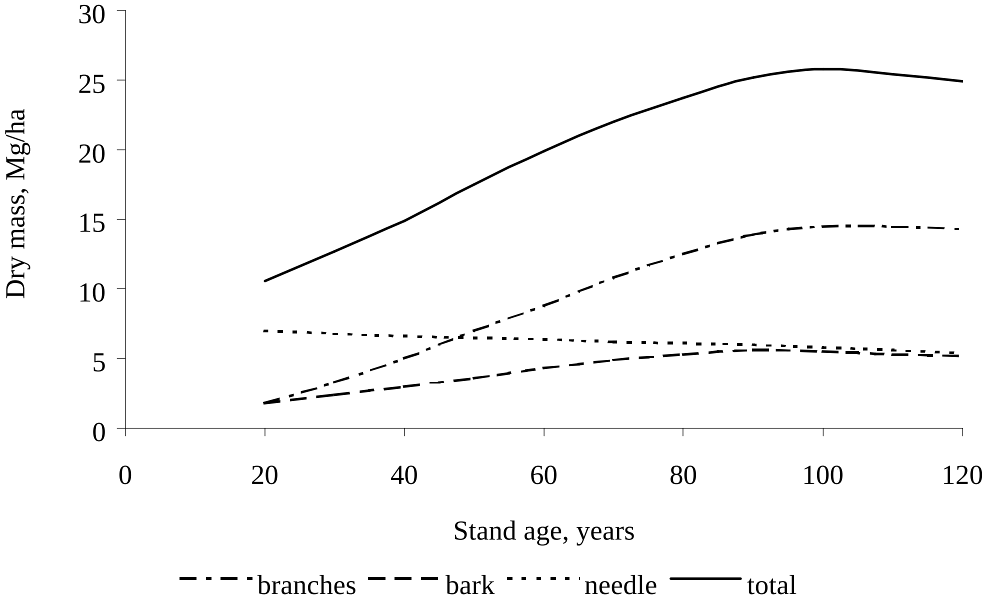

Figure 16. Dynamics of crown mass fractions for the II site class of a normal pine stand in Middle Zavolgie.

The total biomass of the understorey of normal and modal pine stands increases with stand age (Figure 17). The relationship between forest floor and stand age has an S-curve of simple regression with an accumulation of 3 Mg/ha of dry biomass at 110-120 years of age. The undergrowth is better described by the Square root-Y and X equations with a high R^2 coefficient. The accumulation of shrub biomass has a multiplicative and exponential character. As a demonstrative example, the dynamics of crown fractions, understorey and belowground mass (tree roots) for the I site class of modal pine stands is presented in Figure 18.

The results of the simulations for the different forest ecosystem biomass compartments show high productivity potential for the pine stands of Middle Zavolgie. At the end of a simulation of 120 years, the normal stands of the I site class accumulate a 308 Mg/ha total biomass, while the II site modal stands only 213 Mg/ha (Tables 14 and 15, see at the end of the paper). In the modal pine stand of the first site class, at the end of the 120 years, the proportion of stemwood in tree biomass is 65%, woody detritus 11.6%, roots 11 %, branches 7 %, understorey 3.3%, and needles 2 % (Figure 19).

The store of woody detritus in sample plots ranges from 8 m^3/ha or 2 Mg C/ha in young pine forest, to 21 m^3/ha or 4 MgC/ha in middle-aged forest, to 88 m^3/ha or 11.5 MgC/ha in mature forest, to 166 m^3/ha or 16.6 MgC/ha in overmature forest. Within the age groups, the variation is quite high, but the general trend to higher stores of woody detritus in older forests is quite obvious (Figure 20).

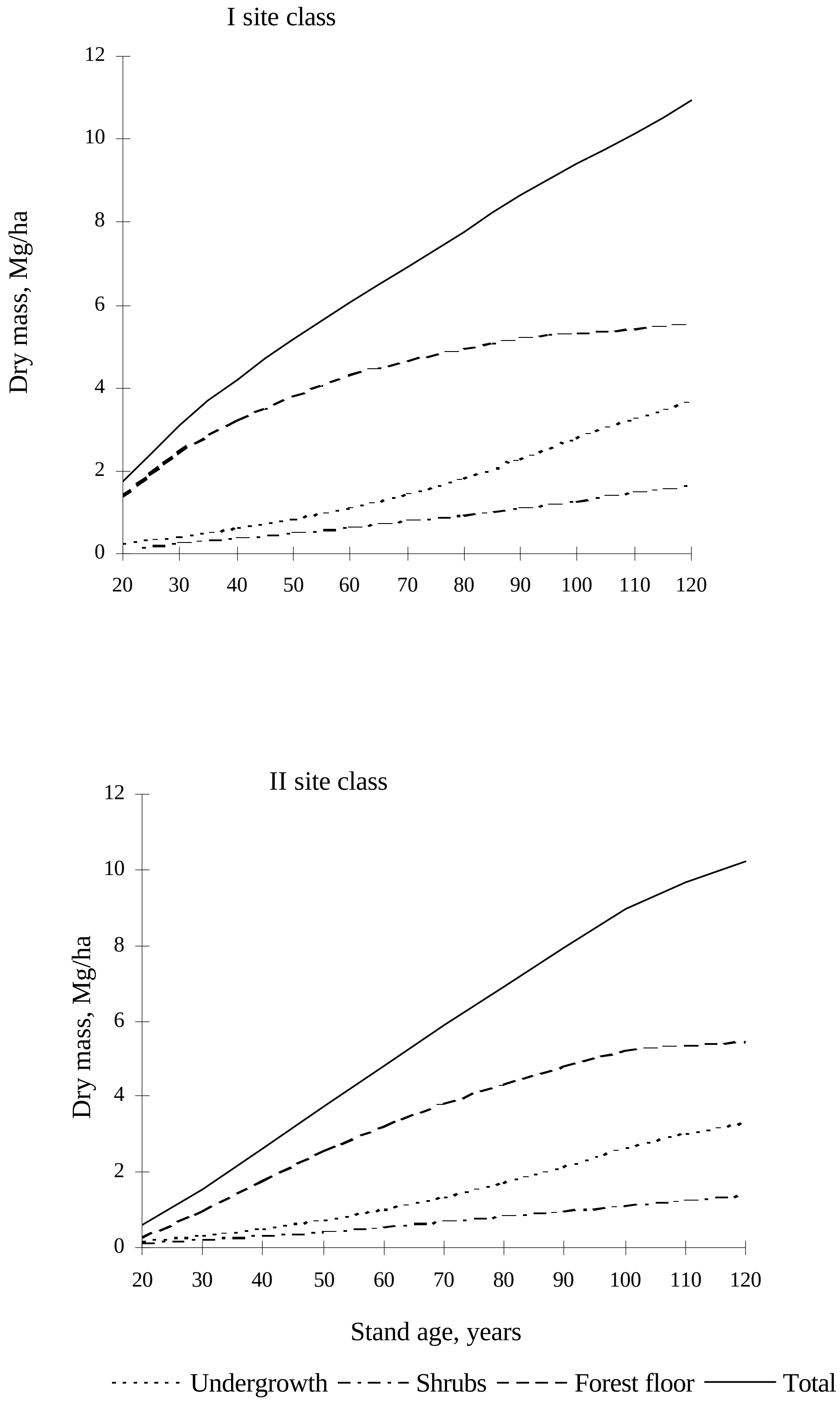

Figure 17. Dynamics of understorey components for the normal pine stands in Middle Zavolgie.

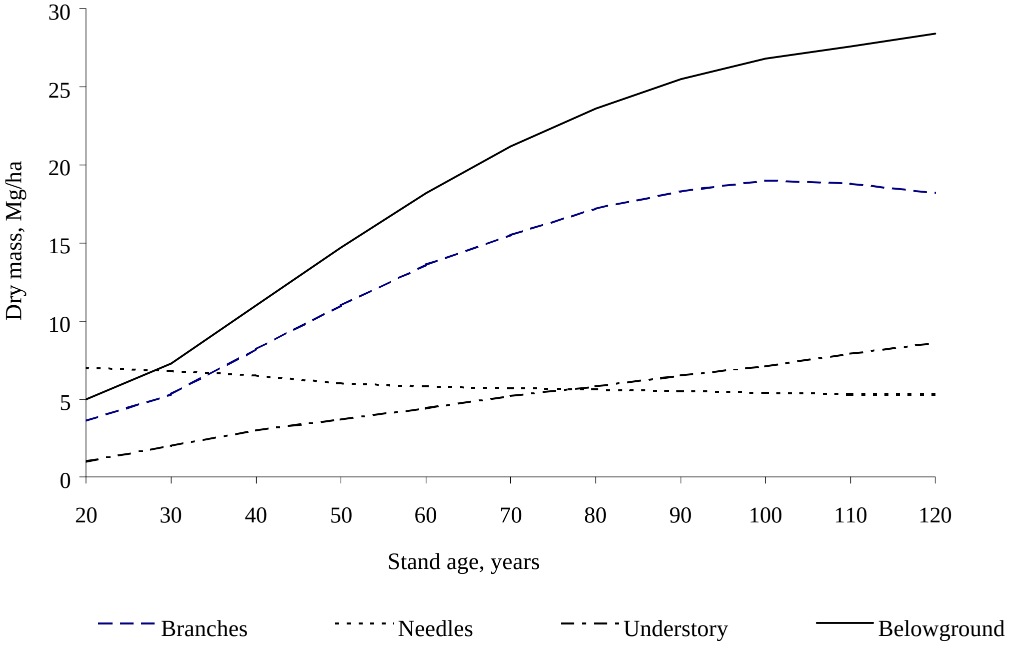

Figure 18. Dynamics of crown, understory and trees belowground mass in the first site class of modal pine stands in Middle Zavolgie.

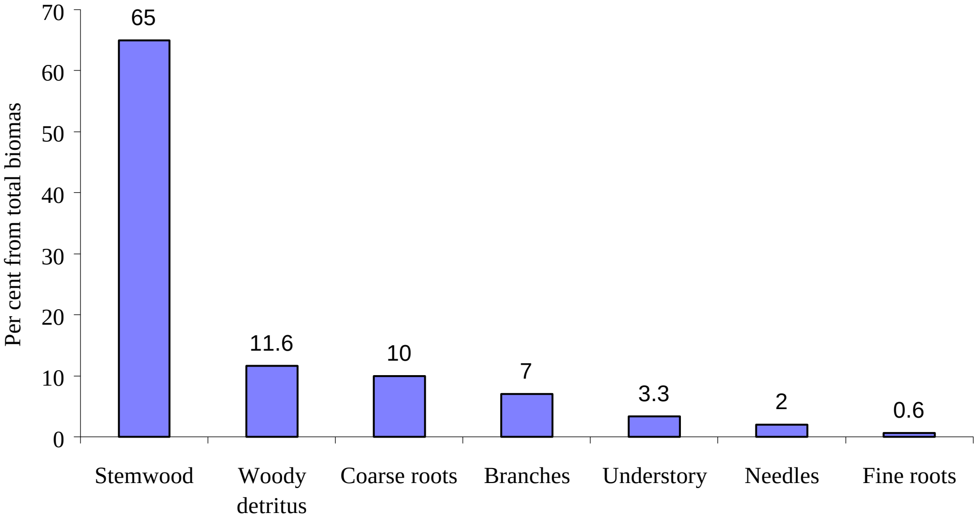

Figure 19. The proportion of biomass components in the I site class in modal pine stands at the end of 120 years simulation.

The amount and proportion of woody detritus were higher in Kirovskaya oblast than in other republics and oblasts in this study (Figure 20). The forests in Kirovskaya oblast are very dense and remote. In such forests, practically no forest management is practised, and, therefore, in some places, the forests contain a large amount of woody detritus.

The average value of the density of wood detritus declines with forest age from 0.25 MgC/m^3 in young forests, 0.19 MgC/m^3 in middle-aged, 0.13 MgC/m^3 in mature to only 0.1 MgC/m^3 in over-mature stands. This reflects the progressively continuing accumulation of decayed material with the ageing of forest. The removal of recently dead trees by salvage is more common in older stands. This also contributes to the declining density of woody detritus material with stand age. The higher density of woody detritus in older stands of Kirovskaya oblast, where woody detritus is not salvaged, supports this conclusion.

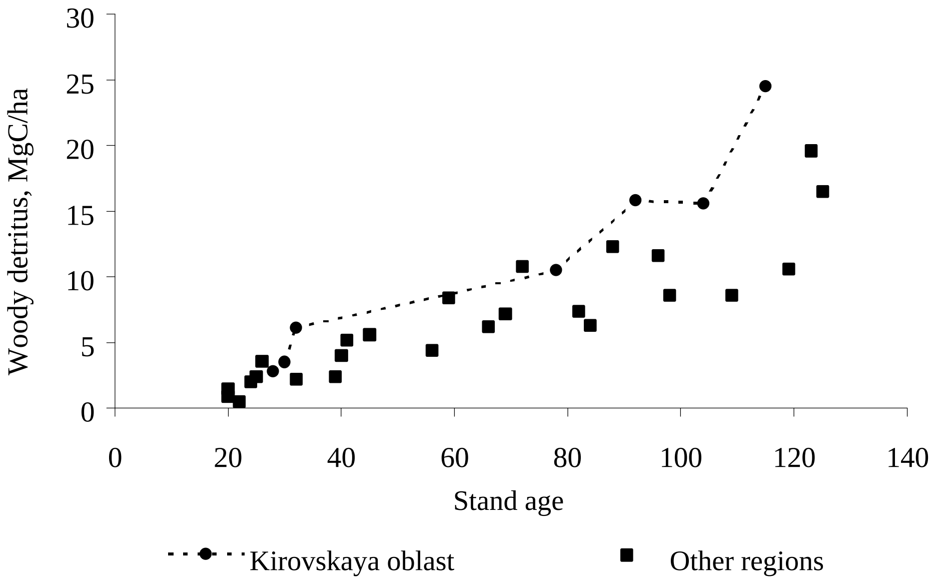

Figure 20. Mass of woody detritus in the sample plots.

5.4 BIOMASS FRACTION RATIO AND MULTIPLE REGRESSION EQUATIONS

Substituting the values of tree fraction indices on relative coefficients with an abundance of generalised characteristics allows us to find general regularities immanent to this abundance and to perform them in a quantitative form. In the 19th century, Flury (1892) has proposed a relative coefficient (biomass ratio) involved with the relationship between biomass components and stemwood volume. The dynamics of the relative coefficients of biomass fractions have more correct tendencies than the dynamics of irrelative values (Usoltcev 1995).

Biomass ratio is of a special interest to the database of Russian forest inventory. Forest inventory in the former USSR has mostly estimated stemwood volumes (Alekseev and Birdsey 1994). For the moment, stem volume can be transformed through biomass ratio to all biomass components.

For further calculations, we applied the relative value, which transforms the growing stock volume of the pine stand to different biomass fractions. For each experimental stand, the ratio of the forest vegetation biomass fraction Rv was calculated according to the formula (Kellomäki et al. 1992):

$Rv = Mv/Vst$,

where Mv is the dry matter weight of biomass fraction in megagrams (Mg) and Vst is the growing stock volume (m^3).

The following biomass components were included in the analysis: Rv(ned) needles; Rv(br) branches (wood and bark of the branches); Rv(st) stems (wood and bark of the stems); Rv(un) understorey biomass (forest floor vegetation, undergrowth and shrubs); Rv(bl) belowground forest stand biomass (coarse roots); Rv(fbl) fine roots; and R(d) woody detritus. The sum of these components formed the total biomass Rv(tot) of the forest ecosystem vegetation. The results of the Rv calculations are presented in Table 16.

In Russia, at present, one of the methods of carbon estimations is connecting relative coefficients or regressive equations to inventory data (Isaev et al. 1995, Alekseev and Birdsey, 1994).

For the determination of the relationship between different biomass fractions, the models of multiple stepwise regression analysis were adjusted with the main inventory material indices. In order to determine the most significant variables, we performed a background stepwise regression, which begins with all the variables in the model and removes them one at a time (Dyuk 1997). Five main forest stand taxation indices were selected to ground further calculations: age (A), mean tree height (H), mean diameter at breast height (D), volume (V) and basal area (B.A.). Table 17 shows the results of applying the multiple regression model with the five pine stand indices to the description of the relationship between pine biomass of branches, needles, stem, understorey, roots (coarse and fine) and woody detritus.

Calculated statistics include the standard error of estimation as the standard deviation of the residuals, the adjusted R^2 values, and p-value that serves as a measure of significance. Larger values of adjusted R^2 correspond to smaller values of the mean square error (MSE). Since the p-value in all models is less than 0.01, the highest order term is statistically significant at the confidence level of 99%. By using these equations with the inventory data it is possible to assess the biomass in pine stands of the Middle Zavolgie region in a high confidence level.

Table 16. Biomass fraction ratio Rv for the first and second site classes of modal and normal pine stands in Middle Zavolgie, Mg of dry matter for each cubic meter of stemwood volume (Mg/m^3).

Age	Needles	Branches	Stemwood	Understorey	Coarse roots	Fine roots	Woody detritus
			I site modal				
20	0.163	0.084	0.479	0.024	0.063	0.053	0.043
30	0.084	0.065	0.468	0.024	0.063	0.027	0.036
40	0.043	0.055	0.422	0.020	0.059	0.014	0.034
50	0.027	0.051	0.413	0.017	0.058	0.009	0.034
60	0.021	0.049	0.409	0.016	0.058	0.007	0.035
70	0.017	0.047	0.406	0.016	0.059	0.006	0.038
80	0.015	0.047	0.404	0.016	0.059	0.005	0.042
90	0.014	0.047	0.402	0.016	0.061	0.005	0.048
100	0.013	0.045	0.400	0.017	0.061	0.004	0.055
110	0.012	0.045	0.399	0.019	0.062	0.004	0.062
120	0.012	0.035	0.398	0.02	0.062	0.004	0.070
			II site modal				
20	0.159	0.077	0.472	0.038	0.067	0.051	0.043
30	0.086	0.061	0.479	0.034	0.065	0.028	0.036
40	0.045	0.052	0.423	0.023	0.061	0.014	0.034
50	0.029	0.049	0.408	0.018	0.06	0.01	0.034
60	0.022	0.047	0.406	0.017	0.059	0.007	0.035
70	0.018	0.046	0.404	0.016	0.06	0.006	0.038
80	0.016	0.046	0.402	0.016	0.061	0.005	0.042
90	0.015	0.047	0.401	0.016	0.062	0.005	0.048
100	0.014	0.046	0.400	0.017	0.063	0.005	0.055
110	0.013	0.043	0.399	0.018	0.064	0.004	0.062
120	0.012	0.041	0.398	0.02	0.064	0.004	0.070
			I site normal				
20	0.155	0.086	0.504	0.035	0.063	0.049	0.039
30	0054	0.049	0.436	0.022	0.056	0.018	0.033
40	0.033	0.044	0.422	0.019	0.055	0.011	0.031
50	0.023	0.041	0.415	0.017	0.055	0.008	0.031
60	0.019	0.041	0.411	0.017	0.055	0.006	0.033
70	0.016	0.041	0.408	0.016	0.056	0.005	0.036
80	0.014	0.040	0.406	0.016	0.057	0.004	0.040
90	0.012	0.040	0.403	0.017	0.057	0.004	0.045
100	0.011	0.039	0.401	0.018	0.058	0.004	0.051
110	0.010	0.037	0.399	0.018	0.058	0.003	0.058
120	0.010	0.035	0.398	0.018	0.059	0.003	0.064
			II site normal				
20	0.167	0.086	0.512	0.014	0.067	0.055	0.039
30	0.065	0.054	0.447	0.013	0.06	0.021	0.033
40	0.038	0.046	0.428	0.015	0.057	0.013	0.031
50	0.028	0.045	0.419	0.016	0.057	0.009	0.031
60	0.022	0.045	0.415	0.016	0.057	0.007	0.033
70	0.018	0.044	0.411	0.017	0.058	0.006	0.036
80	0.015	0.044	0.407	0.017	0.059	0.005	0.040
90	0.013	0.042	0.403	0.018	0.059	0.004	0.045
100	0.012	0.041	0.402	0.018	0.059	0.004	0.051
110	0.011	0.038	0.401	0.019	0.059	0.004	0.058
120	0.010	0.036	0.398	0.019	0.06	0.003	0.064

Table 17. the equations of the relationship between biomass fractions and main taxation indices of the pine stand.

Biomass Fraction, t/ha	Regression equations	R^2	SE	P-value
I site normal stands				
Stem	7.2 - 0.14A + 0.41V	93	0.10	0.000
Branches	2.85 - 0.077A + 0.05V	97	0.46	0.000
Needles	0.34B.A. - 0.02V	95	0.22	0.000
Understorey	0.39 + 0.066A + 0.01V	94	0.12	0.000
Roots	0.35D + 0.04V	93	0.36	0.001
Woody detritus	68.68 + 0.20V - 3.36B.A.	94	2.84	0.001
II site normal stands				
Stem	0.37B.A. + 0.37V	95	0.70	0.000
Branches	0.37A + 1.26D +0.043V	94	0.61	0.001
Needles	0.31B.A. + 0.33 – 0.036V	95	0.29	0.001
Understorey	0.04A - 0.05B.A. + 0.01V	92	0.33	0.000
Roots	0.05B.A. + 0.26D + 0.04V	95	0.09	0.001
Woody detritus	0.39A - 0.71B.A. + 0.76H	92	0.89	0.000
II site modal stands				
Stem	6.19 - 0.035A + 0.39V	94	0.40	0.001
Branches	0.12A + 0.83D + 0.92V	93	0.92	0.000
Needles	7.04 + 0.02D - 0.01V	95	0.08	0.001
Understorey	-0.12 + 0.06A + 0.01V	89	0.62	0.002
Roots	1.71 + 0.19B.A. + 0.047V	92	0.45	0.001
Woody detritus	-6.32 + 0.32A + 0.31B.A. - 0.03V	94	0.96	0.000
II site modal stands				
Stem	9.18 - 0.55H + 0.41V	96	0.38	0.000
Branches	0.07A + 0.32H + 0.04V	95	0.25	0.001
Needles	0.09A + 1.03H - 0.03V	95	0.14	0.000
Understorey	0.45 + 0.06A - 0.001V	89	1.22	0.002
Roots	0.11D + 0.25H + 0.04V	93	0.41	0.001
Woody detritus	0.47A - 1.02H	93	0.12	0.000

5.5 THE CALCULATION OF LITTERFALL

The litterfall pool consists of a turnover of whole stems, needles, branches, coarse and fine roots, and litter from dead trees (woody detritus). In addition, this pool includes material left on the forest floor after each thinning and harvest (brash, stumps and debris). It is assumed that a fraction of the litter decomposes each year, as a result of which a part of it is lost as CO_2 and the remainder is transferred to the soil organic matter pool, where it decomposes more slowly (Cannell 1995).

In Scots pine, the needle litter accounts for the majority of the crown litterfall and has a clear seasonal pattern, with a peak in August-October (Malkonen 1974; Cousens 1988, Finer 1996). As is known from previous studies (Malkonen 1974; Cousens 1988, Finer 1996, Kouki and Hokkanen 1992; Albrektson 1988), no time trend in the amount of needle litterfall exists. The annual needle litterfall is positively correlated with the temperature sum of the growing seasons (Malkonen 1974; Cousens 1988, Finer 1996, Kouki and Hokkanen 1992).

The litterfall of branches and bark increases with stand age (eg. Malkonen 1974; Finer 1996). However, even in mature and overmature stands, the contribution of branches and bark to the litterfall is smaller than that of the needle litter (Finer 1996). Therefore, in our calculations, we assumed that the litterfall of branches and bark is 35% of the needle litterfall. The annual production of needle litter in our simulations was approximately 55% of the total crown biomass (Cousens 1988).

It is assumed that coarse root mortality is associated with a decline in above-ground biomass. In our calculations, we assumed that the turnover of coarse roots is 2% year^{-1}. Fine roots turnover is calculated from the root biomass by using the linear model (Kurz et al. 1996):

$F_{rt} = 0.735 * F_{rb}$,

where F_{rt} is the fine root turnover (Mg/ha/year) and F_{rb} is the fine root biomass (Mg /ha).

According to Russian forestry management, different types of cleaning cuttings are performed during the growth of modal stands (Table 18) (Anuchin 1991). It is assumed that harvested wood would be lost as self-thinning mortality and that it increases the value of the wood harvested in the final cut at the end of rotation. In our simulations, we included this part of wood to the litter pool of modal pine stands.

Table 18. The size of harvested wood during cleaning cuttings, %.

Stand	Type of cleaning cutting		
	Thinnings	Severance felling	Accretion cutting
Pine:			
Pure	10-15	15-20	15-20
Mixed	20-30	20-25	20-25

In thinnings, which are performed in young stands less than 20 years of age, all of the wood remains in the forest for decomposition. Severance felling is usually accomplished when the trees are between 21 and 40 years old. During these cuttings, a proprtion of 40% of the wood is left in the forest and the remaining part, 60%, is used as firewood. Accretion cuttings take place in the middle aged and immature pine stands. Usually, all this wood is taken from the forest for further utilisation, as firewood, for example

In the simulations, all the wood from cleaning cuttings was included in the litter pool of pine stands. By using the obtained fraction ratio of different tree biomass components (Table 16), we calculated the carbon in needles, branches and roots of harvested trees. This part of forest carbon was also included in the litter pool.

5.6 RESPIRATION AND LITTER DECOMPOSITION

The growth and maintenance respiration (Mg C/ha/a) for each biomass fraction of pine stand was calculated in the same way as Karjalainen (1996).

It is generally assumed that the amount of decomposed litter is proportional to the litter pool (Olson 1963). The actual evapo-transpiration, which sums up information on temperature and moisture, has 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 (Kobak 1988; Berg et al. 1993). In the cold conditions of the boreal forests, however, the lack of moisture rarely regulates decomposition, and temperature alone is considered as one of the most important climatic factors affecting the decomposition rate in well-drained soils (Moore 1984).

This dependence of the decomposition rate on the mean annual temperature is likely invalid for the Middle Zavolgie due to the difference in the continentality of the climate. Extremely cold winters of continental climate result in low mean annual 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 summarises the length of the decomposition period and amount of energy for decomposition during that active period (Liski 1997).

6. CARBON BUDGET ASSESSMENTS

6.1 CONVERSION TO CARBON CONTENT

The carbon content of biomass fractions was determined according to Anstet's method that has been modified by Ponomareva and Nikolaeva (Ponomareva et al. 1975). The fractional carbon content of dry woody biomass ranges from 0.47 - 0.58. In further studies, an average value of 0.52 has been used for all biomass components.

6.2 CARBON BUDGET

The sequestration of C in the forest ecosystem was assessed by using a carbon bookkeeping system (C budget) that accounts for the C flows in and out of the forest ecosystem components (Karjalainen 1996). The carbon stock indicates the momentary amount of C in any one component of the system (Table 19). Annual flows (Mg C/ha/a) are rate variables. Cumulative flows (Mg C/ha) describe the accumulation of carbon in the flows over longer periods, for instance, cumulative litterfall, cumulative gross productions, cumulative net production, and so on.

Table 19. A scheme for the calculation of annual and cumulative C flows (Mg C/ha/a and Mg/C/ha) in the pine ecosystems of Middle Zavolgie (Karjalainen 1996).

1. CARBON FLOWS OF VEGETATION

GROSS PRODUCTION: GROWTH (TREES, GROUND VEGETATION) + RESPIRATION
- RESPIRATION: GROWTH AND MAINTENANCE RESPIRATION

= NET PRODUCTION
- LITTERFALL

= NET PRODUCTION OF VEGETATION

2.CARBON FLOWS OF LITTER

FORMATION OF LITTER
- EMISSIONS OF DECAYING LITTER INTO THE ATMOSPHERE
- CHANGE TO SOM (SOIL ORGANIC MATTER)

= NET PRODUCTION OF LITTER

3.CARBON FLOWS OF SOIL ORGANIC MATTER

FORMATION OF SOM (CHANGE OF LITTER TO SOM)
- EMISSIONS OF DECAYING SOM INTO THE ATMOSPHERE

= NET PRODUCTION OF SOM

4.CARBON BALANCE OF FOREST ECOSYSTEM*

C FLOW INTO FOREST ECOSYSTEM (GROSS PRODUCTION)
- C FLOW OUT OF FOREST ECOSYSTEM (RESPIRATION, EMISSIONS OF DECAYING LITTER AND SOM INTO THE ATMOSPHERE)

= NET FOREST ECOSYSTEM PRODUCTION (NEP)

**Is not used in further calculations*

The carbon balance of the whole system, or of one of its components, is a measure showing the system or component (at a given time) acting as a carbon

- ***sink***, if flows to the system or component are greater than flows from the system or component, i.e. net sequestration is positive; or
- ***source***, if flows to the system or component are less than flows from system or component, i.e., net sequestration is negative; or
- the system can be also in ***balance***, neither sink nor source, if flows to the system or component are equal to flows from the system or component.

We calculated the carbon budget for the young (0-40 years), middle-aged (40-60 years), immature (60-80 years), mature and overmature (80 and >) pine stands of Middle Zavolgie. Next, based on these budgets and the pine forest area in the respective age groups (Table 4), we calculated the regional carbon budget total in the pine stands of Middle Zavolgie.

6.3 THE RESULTS OF THE SIMULATIONS

In this study, carbon dynamics were computed at the stand and regional levels. The annual carbon dynamics for the gross production of the different fractions of pine stand are presented in Fig. 21. These curves shown here are consistent with those reported by Karjalainen (1997), who has studied the carbon budget analysis of Siberian Forests.

At the end of a simulation of 120 years, the stand level allocation of carbon in different tree components was similar in both modal and normal pine stands. While stemwood carbon accounted for 55-65% of the carbon stock in pine trees, coarse and fine roots contained 12-22%, branches 8-12%, and needles 4-8% (Fig. 21). The proportion of understorey fraction of the C stock was only 2-6 %.

The study shows that total carbon sequestration varies during pine stand growth, with the maximum rate at 40-70 years of age (Fig. 22). Average gross annual carbon flux is in the range of 1.9 Mg C/ha/a for modal pine stands and 2.5 Mg C/ha/a for normal ones (Table 20). The average annual net ecosystem flux is 1.1 Mg C/ha/a in modal pine stands and 1.5 Mg C/ha/a in normal ones. Litter increases with stand age and has its maximum in 120-year-old normal pine stands (Fig. 22). Litterfall mainly increases on account of woody detritus, which has the largest biomass amount in mature and overmature stands. Taking this into account, carbon sequestration capacity should be assessed in long intervals of forest development by using criteria, such as forest ecosystem net sequestration and carbon stock at the end of a certain time period.

Over the entire 120-year period, differences in emission profiles were noted for different biomass components. As a rule, vegetation respiration varies from 35-40%, litter decay 23-30% and SOM decay 32-45% of the 120-year total C flow to the atmosphere (Tables 21-25).

The accumulation of carbon in different ecosystem stocks of modal pine stands varies in the beginning and after the 120-year simulation. In the 40-year-old modal pine stands, the allocation of C in vegetation stock was 73-75%, in litter 15-17% and in SOM 12-8% (Table 21-25). At the end of the simulation, C accounted for vegetation 65-67%, litter 17-19% and SOM 14-18% (Fig. 23). In normal pine stands, the distribution of carbon during the 120-year simulation was even: 75% in vegetation, 13% in litter and 12% in SOM (Fig. 24).

The total stock of carbon during the 120-year period for the I site modal pine stands is 160 Mg C/ha, which consists of vegetation stock 107 Mg C/ha, litter stock 28 Mg C/ha and SOM stock 25 Mg C/ha (Table 25). The largest total stock of 254 Mg C/ha contains the normal pine stand of the first site.

Of the regions studied, the total C stock in pine ecosystems is higher in Kirovskaya oblast than in other republics and oblasts (Table 26, Fig. 25). The proportion of different stocks of carbon varies with the age of pine stands in Middle Zavolgie. The largest proportion of carbon is contained in young, immature and mature (overmature) stands. In these age groups, the proportion of C stock reaches 19, 20 and 48 % of the carbon stock total of pine stands in Middle Zavolgie (Fig. 25). In immature stands, the percentage of carbon stock in the carbon store total of pine stands of Middle Zavolgie is lower, but is still quite significant. It is relatively stable at about 13%, on average.

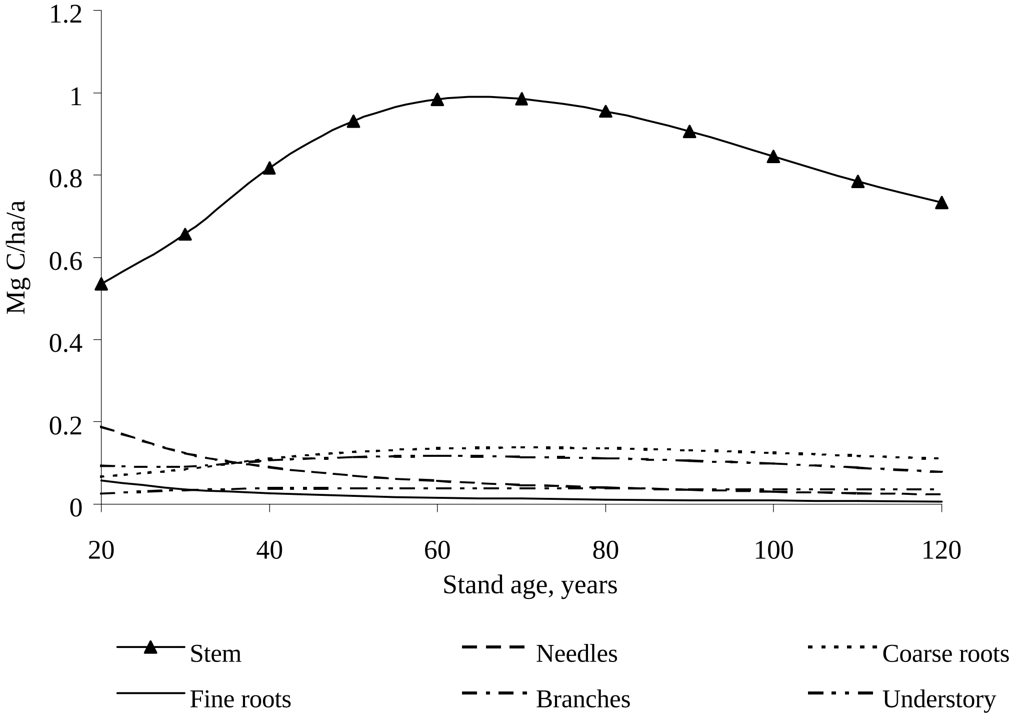

Figure 21. Dynamics of gross carbon production in the first site modal pine stands in Middle Zavolgie

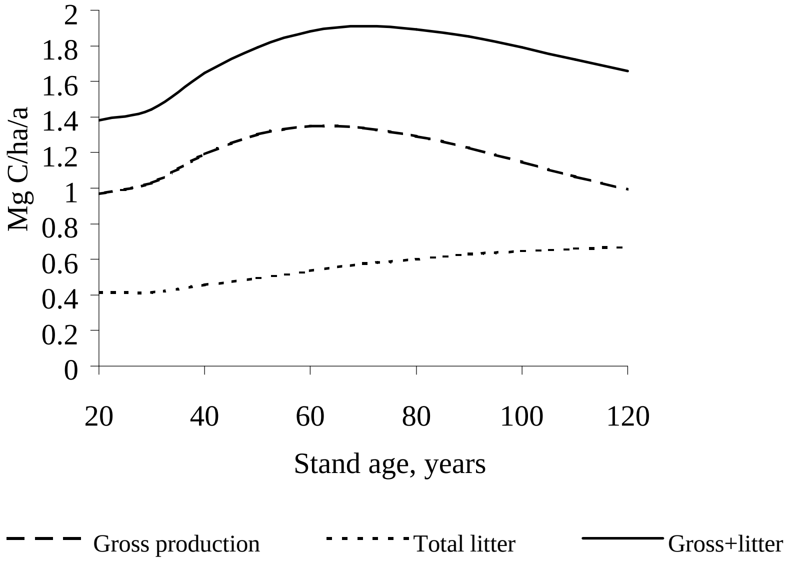

Figure 22. Dynamics of carbon flaxes for the first site of modal pine stands in Middle Zavolgie.

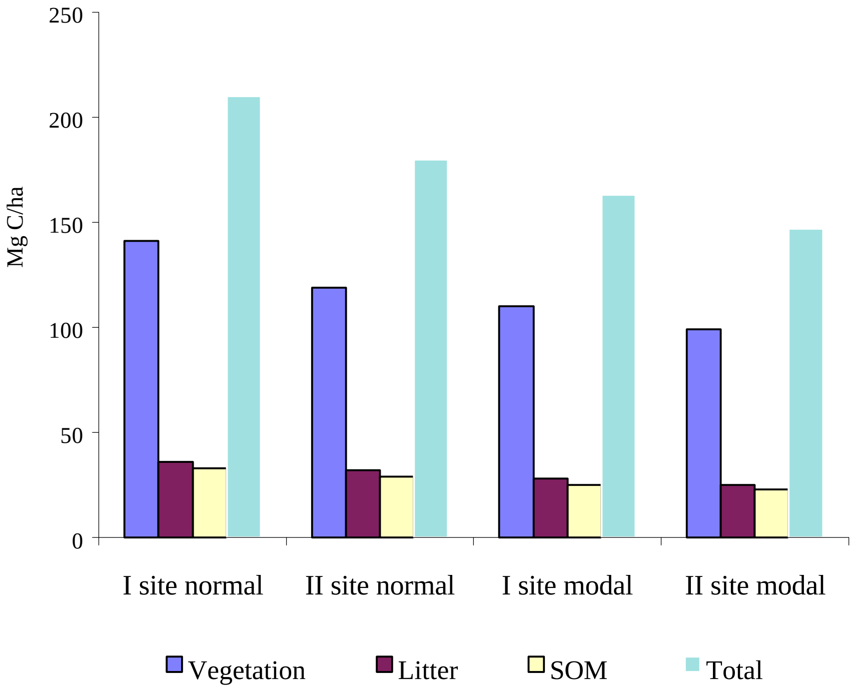

Figure 23. Carbon storages in pine ecosystems after 120 year simulations.

Table 20. Gross and net ecosystem production over 120 years for the pine stands, Mg C/ha/a.

Stand age, Years	Modal I site	Modal II site	Normal I site	Normal II site
Gross ecosystem production				
20	1.8	1.5	2.2	2.0
30	1.9	1.7	3.0	2.5
40	2.4	2.2	3.1	2.6
50	2.6	2.4	3.0	2.7
60	2.4	2.3	2.8	2.6
70	2.2	2.1	2.7	2.5
80	1.9	1.8	2.4	2.5
90	1.7	1.6	2.4	2.2
100	1.5	1.5	2.1	2.1
110	1.4	1.4	2.0	2.0
120	1.4	1.4	1.9	1.8
Net ecosystem production				
20	1.0	0.9	1.5	1.5
30	1.1	1.0	1.8	1.5
40	1.4	1.3	1.9	1.6
50	1.5	1.4	1.8	1.6
60	1.4	1.3	1.7	1.6
70	1.3	1.2	1.6	1.5
80	1.2	1.1	1.5	1.5
90	1.0	1.0	1.4	1.3
100	0.9	0.8	1.3	1.3
110	0.8	0.8	1.2	1.2
120	0.8	0.8	1.1	1.1

The regional carbon budget of the pine forests was 128.4 TgC. While Kirovskaya oblast contains the largest proportion of this carbon stock total in Middle Zavolgie - 70 TgC, Tatarstan has only 5.2 TgC (Table 26). The pine stands of Nizegorodskaya oblast and Republic Mari El have 37.4 TgC and 15.8 TgC of the carbon stores respectively (Fig. 25).

Table 21. Carbon budget for the young normal and modal pine stands in Middle Zavolgie. Cumulative C flows are shown for 40 years and stocks after a 40-year simulation.

Mg C/ha	Modal I site	Modal II site	Normal I site	Normal II site
Gross Production	94	84	128	106
- Respiration	32	29	44	36
= Net production	62	55	84	70
- Litterfall	48	43	61	51
= **Vegetation stock**	**14**	**12**	**23**	**19**
Formation of litter	48	43	61	51
-Into the atmosphere	19	18	24	21
- Change to SOM	26	23	33	27
= **Litter stock**	**3**	**2**	**4**	**3**
Formation of SOM	26	23	33	27
-Into the atmosphere	24	21	30	24
= **SOM stock**	**2**	**2**	**3**	**3**
Total stock	**19**	**16**	**30**	**25**

Table 22. Carbon budget for middle-aged normal and modal pine stands in Middle Zavolgie. Cumulative C flows are shown for 60 years and stocks after a 60-year simulation.

Mg C/ha	Modal I site	Modal II site	Normal I site	Normal II site
Gross Production	234	211	309	257
- Respiration	80	72	105	88
= Net production	154	139	204	169
- Litterfall	130	118	149	123
= **Vegetation stock**	**24**	**21**	**55**	**46**
Formation of litter	130	118	149	123
-Into the atmosphere	52	47	60	50
- Change to SOM	70	64	80	66
= **Litter stock**	**8**	**7**	**9**	**7**
Formation of SOM	70	64	80	67
-Into the atmosphere	64	58	72	60
= **SOM stock**	**6**	**6**	**8**	**7**
Total stock	**38**	**34**	**72**	**60**

Table 23. Carbon budget for the immature normal and modal pine stands in Middle Zavolgie. Cumulative C flows are shown for 80 years and stocks after an 80-year simulation.

Mg C/ha	Modal I site	Modal II site	Normal I site	Normal II site
Gross Production	424	384	548	465
- Respiration	144	130	186	158
= Net production	280	254	362	307
- Litterfall	246	224	267	227
= **Vegetation stock**	**34**	**30**	**95**	**80**
Formation of litter	246	224	267	227
-Into the atmosphere	98	90	107	91
- Change to SOM	133	121	144	122
= **Litter stock**	**15**	**13**	**16**	**14**
Formation of SOM	133	120	144	122
-Into the atmosphere	120	108	130	110
= **SOM stock**	**13**	**12**	**14**	**12**
Total stock	**62**	**55**	**125**	**106**

Table 24. The carbon budget for the mature and overmature normal and modal pine stands in Middle Zavolgie. Cumulative C flows are shown for 100 years and stocks after a 100-year simulation.

Mg C/ha	Modal I site	Modal II site	Normal I site	Normal II site
Gross Production	641	580	827	716
- Respiration	218	197	281	244
= Net production	423	383	546	472
- Litterfall	354	320	405	351
= **Vegetation stock**	**69**	**63**	**141**	**121**
Formation of litter	354	320	405	351
-Into the atmosphere	141	128	162	140
- Change to SOM	191	173	219	190
= **Litter stock**	**22**	**19**	**24**	**21**
Formation of SOM	191	173	219	189
-Into the atmosphere	172	156	197	170
= **SOM stock**	**19**	**17**	**22**	**19**
Total stock	**110**	**99**	**187**	**161**

Table 25. Carbon budget for normal and modal pine stands in Middle Zavolgie. Cumulative C flows are shown for 120 years and stocks after a 120-year simulation.

Mg C/ha	**Modal I site**	**Modal II site**	**Normal I site**	**Normal II site**
Gross Production	868	789	1130	995
- Respiration	295	268	384	338
= Net production	573	521	746	656
- Litterfall	466	424	555	489
= **Vegetation stock**	**107**	**97**	**191**	**167**
Formation of litter	466	424	555	489
-Into the atmosphere	186	169	222	196
- Change to SOM	252	230	300	264
= **Litter stock**	**28**	**25**	**33**	**29**
Formation of SOM	252	230	300	264
-Into the atmosphere	227	207	270	238
= **SOM stock**	**25**	**23**	**30**	**26**
Total stock	**160**	**145**	**254**	**222**

Table 26. Carbon budget for the pine ecosystems in Middle Zavolgie (287000 km^2), GgC.

Republic, oblast	Young stands	Middle-aged stands	Immature stands	Mature and overmature stands	Total
Vegetation					
Nizegorodskaya oblast	8388	5817	3990	6048	24243
Kirovskaya oblast	5940	6363	3720	28602	44625
Mari El	2712	2667	1350	3402	10131
Tatarstan	1140	798	360	1134	3432
Subtotal	18180	15645	9420	39186	82431
Litter					
Nizegorodskaya oblast	1398	1939	1729	1824	6890
Kirovskaya oblast	990	2121	1612	8626	13349
Mari El	452	889	585	1026	2952
Tatarstan	190	266	156	342	954
Subtotal	3030	5215	4082	11818	24145
SOM					
Nizegorodskaya oblast	1398	1662	1596	1632	6288
Kirovskaya oblast	990	1818	1488	7718	12014
Mari El	452	762	540	918	2672
Tatarstan	190	228	144	306	868
Subtotal	3030	4470	3768	10574	21842
Total					
Nizegorodskaya oblast	11184	9418	7315	9504	37421
Kirovskaya oblast	7920	10302	6820	44946	69988
Mari El	3616	4318	2475	5346	15755
Tatarstan	1520	1292	660	1782	5254
Total	**24240**	**25330**	**17270**	**61578**	**128418**

6.4 CONCLUSIONS AND DISCUSSION

This study shows that the pine ecosystems of Middle Zavolgie make a positive and significant contribution to carbon sequestration in Russia. The pine forests of the region of Middle Zavolgie in Russia store large amounts of carbon in vegetation (82.4 TgC), litter (24.1 TgC) and SOM (21.8 TgC) with a considerable stock rate over 120 years. The predominance of young and middle-aged stands stipulates high sequestration abilities of pine ecosystems in the region (Table 4).

For the assessment of carbon budget at the stand and ecoregional level, it is necessary to evaluate the biomass of all forest stand components. For the carbon budget estimation of the pine stands of Middle Zavolgie, the materials of 96 sample plots were used. These were established in the Republic Mari El, Tatarstan, Nishegorodskaya and Kirovskaya oblast. On the data of sample plots, simple and multiple regression equations to describe the relationship between biomass components and main forest taxation indices were developed. Mitscherlich’s function was used for a pine stemwood development simulation.

Overall, it should be said that the approximation of taxation index dynamics for pine stands has produced good results with the help of Mitscherlikh’s function. The only drawback is the fact that the function has an asymptote parallel to the age axis and, therefore, is considered to be strictly increasing. Therefore, its application is limited by the age of natural maturity when the growth decreases.

All the results show an adequate description of biomass allocation in the pine stands. The approximation of the biomass components in relation with the diameter and the stand age confirms a plausible consequence (the value of R^2 is between 85 and 95 %). All the regularities obtained allow estimating the biomass of all pine stands in Middle Zavolgie by connecting them with the data from the forest inventory.

The sequestration of carbon in pine stands of Middle Zavolgie was assessed by using a C bookkeeping system (Karjalainen, 1996; Karjalainen, 1997). The results of this study were compared with various other studies. They are generally within the range of those reported for other forest regions and countries. In our calculations, the average NEP for 120-year modal and normal pine stands was 1.3 and 1.6 MgC/ha/a. In the Russian Federation, the gross production for conifer stands reaches 1.6 MgC/ha/a (Isaev et al. 1995). Nabuurs and Mohren (1995) have reported the net annual carbon stock flux for slow-growing long rotation forests to be 1 Mg C/ha/a. In Britain, the net annual carbon flux for Scots pine over the first rotation including trees, products, litter and soil was estimated in a rate of 2.7 MgC/ha/a (Cannell and Milne 1995). Differences in the results can be explained by the difference in the forest types, climate, site productivity and the level of forest management.

The carbon budget of the I and II site modal pine stands in Middle Zavolgie (160 MgC/ha and 145MgC/ha) are in accordance with results reported for Scots pine by Karjalainen (1996), who has studied C budget for Finnish forests. After a 200-year simulation, he reports the stocks for unmanaged Scots pine stands for southern Finland to be 178 MgC/ha and for northern Finland 163 MgC/ha.

Carbon sequestration is higher in normal pine stands than in modal ones, if evaluated to the end of the investigated period (up to 120 years), which confirms the high potential productivity of the

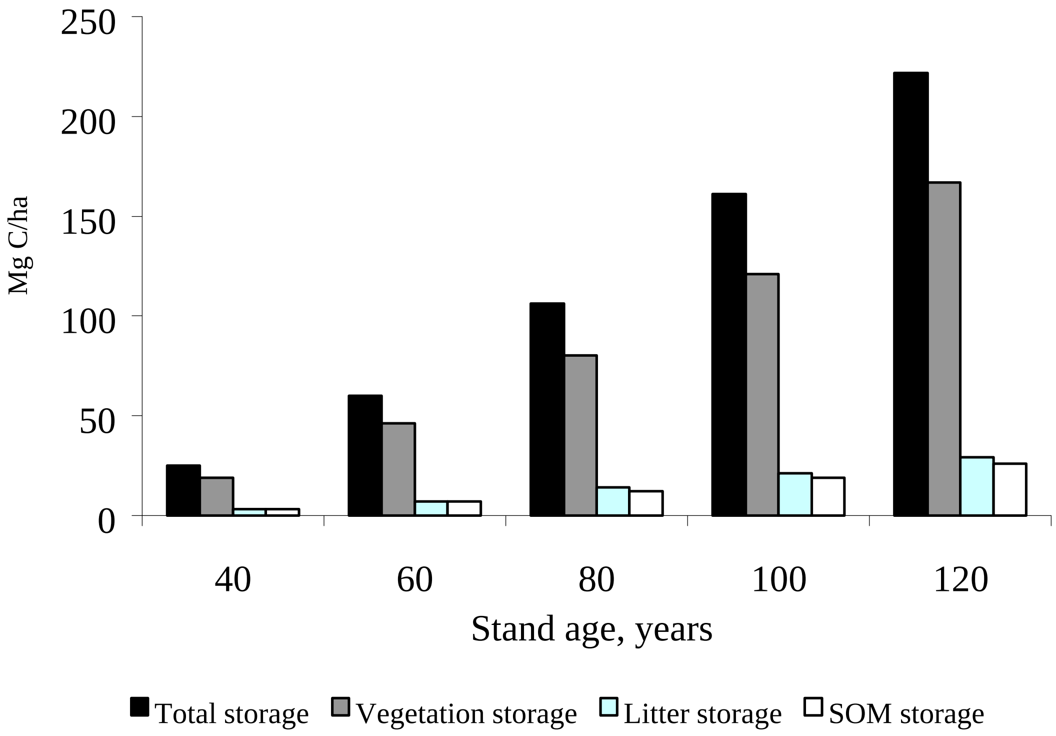

Figure 24. Development of carbon storages in I site normal pine stands in Middle Zavolgie.

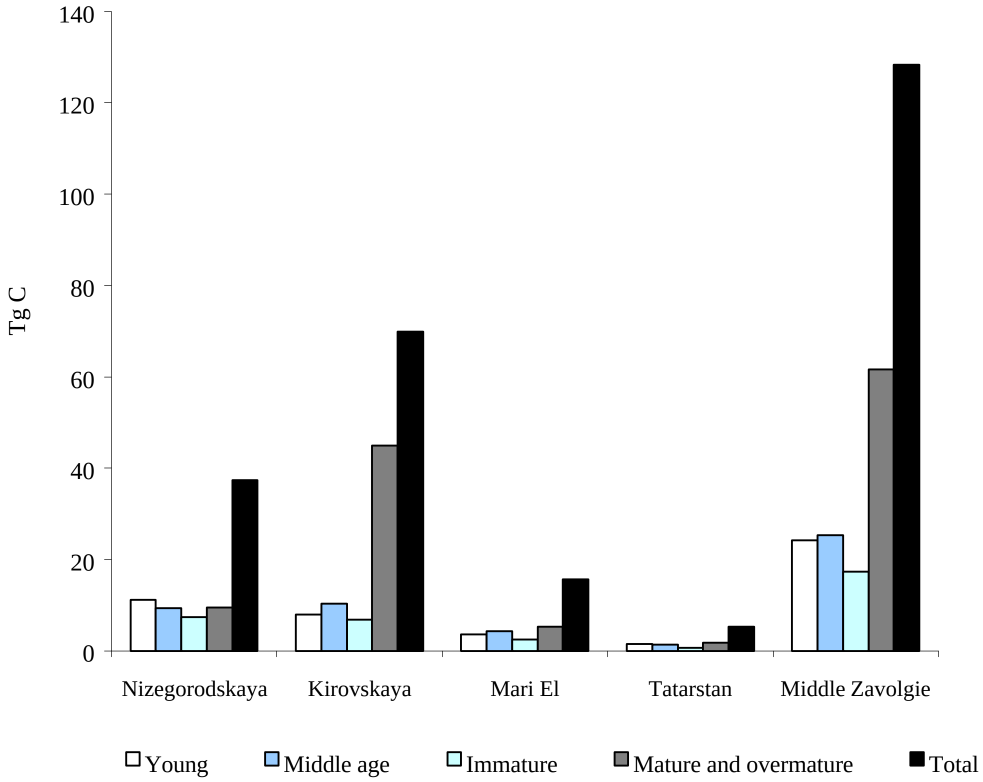

Figure 25. Carbon storages by age groups in republics and oblasts of Middle Zavolgie.

fully stocked normal stands. Nevertheless, more attention should be paid to modal pine stands, because they are more prevalent in the nature.

The biomass of woody detritus varies considerably in all age classes, especially in middle-aged and mature stands. Even within the limits of the same species, the process of tree mortality is not uniform and is highly dependent on local soil and climatic conditions (Morozov 1949). The better these conditions, the earlier and faster is the process of natural thinning. Due to the shade-intolerance of pine, its stands thin rapidly, especially when they are young or middle-aged.

The considerable variation of organic matter of the woody detritus in the pine stands might be explained by several reasons:

- The sample plots have been established in stands of different forest types and site conditions.
- Practically all of them have been subject to different types of commercial cuttings ranging from thinnings to salvage logging.
- There are stands subject to different kinds of diseases including *Fomitopsis annosa* and Melolontha.
- Different levels of forest management intensity in the republic of Mari El and Tatarstan (high level) and Kirovskaya and Nizegorodskaya oblasts (low level).
- Time has elapsed since the felling and species-specific factors, such as decay resistance (Harmon et al. 1986).
- The process of tree mortality has been rather stochastic contributing to random variation.

Our results for the pine stands of the region of Middle Zavolgie in Russia are generally within the range of those reported by other writers. In north-western Russia, dead wood stores range from 1-8 MgC/ha in young and mature intensively managed stands, to 17 MgC/ha in old-growth forests (Krankina and Harmon 1995). In our calculations for mature and overmature stands, woody detritus is 6-24 Mg C/ha. In undisturbed dry tropical forests, these stores reach 9-21 Mg Ñ/ha (Harmon et al. 1986), in cold deciduous forests 15-25 Mg C/ha (Gore and Patterson 1986; Harmon et al. 1986) and in pine stands of the temperate conifer forests 4-21 MgÑ/ha (Harmon et al. 1986).

This study on the stand level analysis of pine stands forms the basis for further methods of regional assessments. However, several considerations should be taken into account. The regression equations obtained are only for pure even-aged stands of the I and II classes. The proportion of mixed pine stands can be significant. Therefore, the assessment of significant parts of mixed species pine stands for all site classes requires additional research in this type of forest ecosystems or the use of a correction factor for mixed species. Forest fires should be considered in more detail by taking into account the climatic conditions and the frequency of the fires on the investigated territory.

The part of biomass removed from the forest as wood-based products should also be taken into account (Karjalainen et al. 1994; Kurz et al. 1992), as well as insect outbreaks and diseases, which can be considered as disturbances too (Isaev et al. 1995). All these corrections might facilitate more precise carbon estimations at the stand and regional levels.

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Table 14. Biomass dynamics in the modal pine stands in the Middle Zavolgie, Mg/ha (dry mass).

Stand age, years	Crown fractions				Stemwood			Understory				Belowground of pine trees			Woody detritus
	Branches	Bark	Needles	Total	Stem	Bark	Total	Under-growth	Shrubs	Forest floor	Total	Coarse roots	Fine roots	Total	
I site class															
20	1.8	1.8	7.0	10.6	16.5	4.1	20.6	0.1	0.01	0.9	1.0	2.7	2.3	5.0	1.7
30	2.9	2.4	6.8	12.1	32.7	5.2	37.9	0.2	0.03	1.8	2.0	5.1	2.2	7.3	3.2
40	5.1	3.1	6.5	14.7	56.8	6.1	62.9	0.4	0.07	2.5	3.0	8.9	2.1	11.0	5.1
50	7.4	3.6	6.0	17.0	82.7	6.9	89.6	0.6	0.1	3.0	3.7	12.7	2.0	14.7	7.3
60	9.6	4.0	5.8	19.4	105.9	7.7	113.6	0.8	0.2	3.4	4.4	16.3	1.9	18.2	9.8
70	11.2	4.3	5.7	21.2	124.6	8.0	132.6	1.1	0.3	3.8	5.2	19.3	1.9	21.2	12.5
80	12.6	4.6	5.6	22.8	138.7	8.2	146.9	1.4	0.4	4.0	5.8	21.8	1.8	23.6	15.5
90	13.6	4.7	5.5	23.8	148.6	8.2	156.8	1.7	0.5	4.3	6.5	23.7	1.8	25.5	18.8
100	14.4	4.6	5.4	24.5	154.7	7.9	162.6	2.0	0.7	4.4	7.1	25.0	1.8	26.8	22.2
110	14.4	4.4	5.3	24.1	158.5	7.6	166.1	2.5	0.8	4.6	7.9	25.9	1.7	27.6	25.8
120	14.2	4.0	5.3	23.5	161.9	7.4	169.3	2.9	1.0	4.8	8.6	26.7	1.7	28.4	29.7
II site class															
20	1.4	1.6	6.2	9.2	14.6	3.8	18.4	0.08	0.02	1.4	1.5	2.6	2.0	4.6	1.7
30	2.3	2.0	6.1	10.4	29.3	4.7	34.0	0.18	0.03	2.2	2.4	4.6	2.0	6.6	3.2
40	4.3	2.6	5.9	12.8	50.3	5.6	55.9	0.30	0.05	2.7	3.0	8.1	1.9	10.0	5.1
50	6.4	3.2	5.8	15.4	74.2	6.3	80.5	0.47	0.07	3.1	3.5	11.7	1.9	13.6	7.3
60	8.2	3.6	5.6	17.4	95.6	7.0	102.6	0.67	0.10	3.4	4.2	15.0	1.8	16.8	9.8
70	9.6	3.9	5.4	18.9	112.8	7.5	120.3	0.91	0.15	3.6	4.6	17.9	1.8	19.7	12.5
80	11.1	4.2	5.3	20.6	125.7	7.6	133.3	1.2	0.23	3.8	5.2	20.2	1.7	21.9	15.5
90	12.2	4.3	5.2	21.7	134.5	7.6	142.1	1.5	0.35	3.9	5.8	21.9	1.7	23.6	18.8
100	12.5	4.2	5.1	21.8	139.4	7.4	146.8	1.8	0.52	4.0	6.3	23.1	1.7	24.8	22.2
110	12.4	4.0	4.9	21.3	144.4	7.2	151.6	2.2	0.77	4.1	7.1	24.1	1.6	25.7	25.8
120	12.3	3.8	4.9	21.0	150.5	6.8	157.3	2.6	1.20	4.1	7.9	25.2	1.6	26.8	29.7

Table 15. Biomass dynamics in the normal pine stands in the Middle Zavolgie, Mg/ha (dry mass).

Stand age, years	Crown fractions				Stemwood			Understory				Belowground of pine trees			Woody detritus
	Branches	Bark	Needles	Total	Stem	Bark	Total	Under-growth	Shrubs	Forest floor	Total	Coarse roots	Fine roots	Total	
I site class															
20	2.2	2.0	7.4	11.8	18.7	6.0	24.7	0.3	0.1	1.3	1.7	3.1	2.4	5.5	1.9
30	3.8	2.8	7.3	13.9	51.4	7.4	58.8	0.4	0.2	2.4	3.0	7.6	2.4	10.0	4.4
40	5.8	3.7	7.1	16.6	82.3	8.8	91.1	0.6	0.4	3.2	4.2	11.9	2.3	14.2	6.7
50	7.9	4.2	6.8	18.9	111.6	9.9	121.5	0.8	0.5	3.8	5.1	16.1	2.2	18.3	9.2
60	9.8	4.8	6.7	21.3	137.5	10.8	148.3	1.1	0.6	4.3	6.0	20.0	2.2	22.2	12.0
70	11.6	5.4	6.5	23.5	159.6	11.3	170.9	1.4	0.8	4.7	6.9	23.5	2.1	25.6	15.3
80	13.0	5.9	6.4	25.3	178.3	11.5	189.9	1.8	0.9	4.9	7.6	26.6	2.1	28.7	18.9
90	14.4	6.1	6.2	26.7	193.6	11.4	205.0	2.3	1.1	5.2	8.6	29.2	2.0	31.2	23.1
100	15.2	5.9	6.0	27.0	206.1	11.0	217.1	2.9	1.3	5.3	9.5	31.3	1.9	33.2	27.7
110	15.2	5.7	5.8	26.7	216.0	10.4	226.4	3.4	1.5	5.4	10.3	33.1	1.9	35.0	32.7
120	15.0	5.4	5.7	26.1	224.0	10.0	234.4	3.6	1.7	5.5	10.8	34.5	1.8	36.3	37.9
II site class															
20	1.8	1.8	7.0	10.6	16.0	5.5	21.5	0.2	0.1	0.3	0.6	2.8	2.3	5.1	1.9
30	3.3	2.4	6.8	12.5	40.0	6.9	46.9	0.3	0.2	0.9	1.4	6.3	2.2	8.5	4.4
40	5.0	3.0	6.7	14.7	66.3	8.1	74.4	0.5	0.3	1.8	2.6	10.0	2.2	12.2	6.7
50	7.0	3.6	6.5	17.1	89.9	9.1	99.0	0.7	0.4	2.6	3.7	13.6	2.1	15.7	9.2
60	9.2	4.3	6.4	19.9	112.8	10.0	122.8	1.0	0.6	3.2	4.8	17.1	2.1	19.2	12.0
70	10.8	4.9	6.3	22.0	134.5	10.5	145.0	1.4	0.7	3.8	5.9	20.5	2.1	22.6	15.3
80	12.5	5.3	6.2	24.0	153.9	10.7	164.6	1.7	0.8	4.4	6.9	23.7	2.0	25.7	18.9
90	13.6	5.6	6.0	25.2	168.8	10.6	179.4	2.2	0.9	4.8	7.9	26.5	1.9	28.4	23.1
100	14.5	5.5	5.8	25.8	185.2	10.3	195.5	2.6	1.1	5.2	8.9	28.8	1.9	30.7	27.7
110	14.5	5.3	5.6	25.4	196.6	10.0	206.6	3.2	1.2	5.3	9.7	30.7	1.8	32.5	32.7
120	14.3	5.2	5.4	24.9	205.0	9.6	214.6	3.5	1.4	5.4	10.3	32.1	1.7	33.8	37.9