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Possibilities for Increased Carbon Sequestration through the Implementation of Rational Forest Management in Russia

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FOREWORD

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

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

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

The study is now moving into its second phase, which will encompass assessment studies of the greenhouse gas balances, forest resources and forest utilization, biodiversity and landscapes, non-wood products and functions, environmental status, transportation infrastructure, forest industry and markets, and socio-economics. This report, carried out by Professors Shvidenko and Nilsson from the study's core team and Professor Roshkov from the Dokuchajev Soil Institute Moscow is a contribution to the analyses of the topic of greenhouse gas balances.

POSSIBILITIES FOR INCREASED CARBON SEQUESTRATION THROUGH THE IMPLEMENTATION OF RATIONAL FOREST MANAGEMENT IN RUSSIA

ANATOLY SHVIDENKO[1], STEN NILSSON[1] and VJACHESLAW ROJKOV[2]

Abstract. Huge areas of the Russian forests suffer from insufficient forest management. A scenario has been developed for an improved management program that would be implemented over the next 40 years. Possible options have been aggregated into three interlinked groups: increase in forest productivity through improvement of the forest conditions and the structure of the Forest Fund, decrease of carbon by mitigation of disturbance regimes, and improvement of landscape management. One prerequisite in developing this scenario was that the cost of sequestering one ton of carbon should not exceed US$3 (1992 dollar value). In this article a simple model is described to illustrate the following possibilities for increased carbon fixation by improved forest management: large-scale reforestation and afforestation, replacement of stands with low productivity and replacement of so called soft deciduous species and "climax" stands, and implementation of rational silviculture (thinning). The results indicate a potential for an increase in carbon fixation in Russian forest ecosystems of 24.4 Pg over 100 years, after the first year that the actions discussed are implemented. The net sink of carbon was determined to be 16.5 Pg in the low estimate and 42.5 Pg in the high estimate. However, there are many uncertainties in the data and there are difficulties in adequately modeling the possibilities for implementation under current conditions in Russia. In spite of these uncertainties we conclude that there is great potential for economically justified increased carbon fixation through improved forest management in Russia.
Key words: carbon budget, forest management, climate change, and mitigation options.

1. Introduction

The Russian forests comprise more than 20% of the world's forest cover and could play an important role in the mitigation of foreseen climate change. According to the Forest State Account (FSA), the Forested Area (see definition in Appendix 1) in Russia increased by 57.9 million ha during the period from 1966 to 1993 reaching a total of 763.5 million ha in 1993. The growing stock of stemwood (over bark) increased by 3.7 billion m^3 during this period (Gosleshoz, 1968; Goskomles, 1989; 1990a, 1991a; FSFM, 1994). Nevertheless, recent

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detailed analyses (Nilsson *et al.*, 1992; Shvidenko and Nilsson, 1994) show that the current states of the forest resources and forest management in Russia are not satisfactory. A serious negative development has taken place during the period from 1983 to 1993: the Forested Area decreased by 3.1 million ha, and the growing stock of stemwood decreased by 1.3 billion m^3. It can be concluded that these developments do not correspond with the requirements of sustainable development (e.g. Ramakrishna and Woodwell, 1993). The main reasons for the decline are forest fires, outbreaks of insects and diseases, unsatisfactory forest management, and negative anthropogenic impacts (Isaev, 1991a, 1991b; Nilsson *et al.*, 1992; Shvidenko, 1994).

To estimate the net carbon (C) fixation that would result from improved forest management, the relevant management options must be structured. In addition, the temporal and spatial scales must be defined and an appropriate model for the analyses must be employed. A simplified structure of the options is presented in *Figure 1*. Three major groups of options

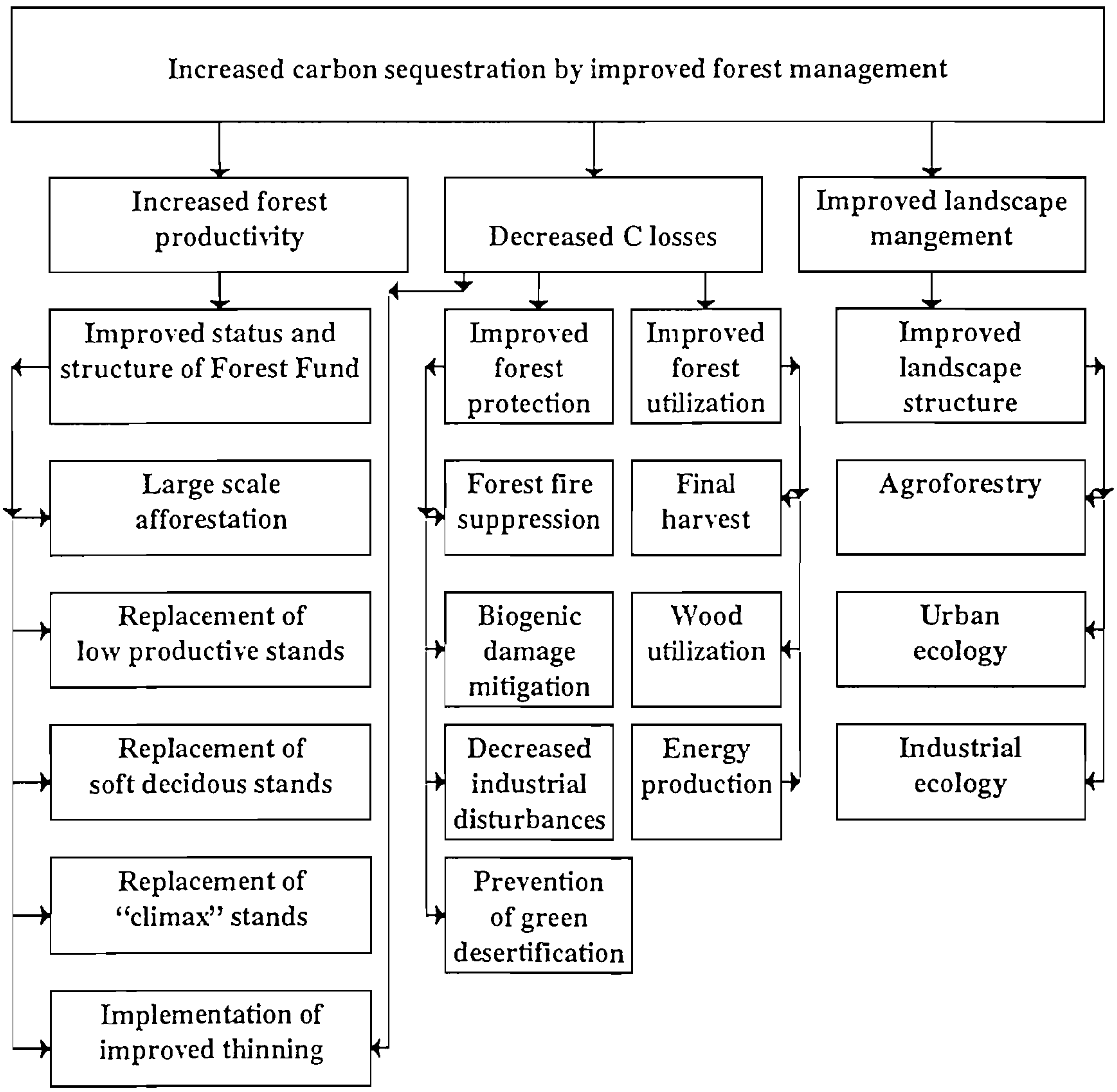

Figure 1. General scheme for increased carbon sequestration by improved management.

(increased forest productivity, decreased C losses, and improved landscape management) are interlinked and interdependent. In this article, we only consider the options dealing with the improvement of the state and structure of the Forest Fund. Decreased C losses by improved forest protection will be dealt with in an upcoming article.

The objective of the analyses is to present a large-scale aggregated estimate for all of Russia. One hundred forty-one ecoregions for Russia have been employed as primary units in the analyses (Shvidenko *et al.*, 1994). In some of the analytical steps, these ecoregions have been aggregated into zonal (latitudinal) and longitudinal vegetational regions. This latter aggregation is illustrated in *Table I.*

The temporal horizon in the analyses is defined by the period of possible implementation of the forest management activities proposed and by the average time in which the impacts of the implementation would be maximized.

The model employed in the analyses must account for accumulative functions of C fixation based on nonlinear growth of biomass (net ecosystem productivity), soil organic matter and detritus dynamics, the utilization of forest products harvested, etc. The model must be developed for each homogeneous group of the options identified and must take probable uncertainties into account.

TABLE I

Data on Russian forests by vegetational zones. Areas are given in million ha and growing stock in m^3 per ha.

Zone	TLA	FF	FL	FA	AGS
SA&T	293.0	111.2	7.1	—	—
FT&SpT&MdF	291.2	229.4	185.7	135.7	65
NT	125.6	123.3	78.7	66.3	110
MT	385.9	381.0	334.2	320.0	120
ST	232.1	219.0	176.8	157.3	145
MxF&DF&FS	242.7	109.2	93.7	85.6	155
S&SD&D	104.3	9.5	7.9	6.2	70
Total	1674.8	1182.6	884.1	771.1	111

Abbreviations:
Zones: SA&T = Subarctic + tundra; FT&SpT&MdF = Forest tundra + sparse taiga + meadow forests; NT, MT and ST = northern, middle, and southern taiga respectively, MxF&DF&FS = mixed forests + deciduous forests + forest steppe; S&SD&D = steppe + semidesert + desert.
Indicators: TLA, FF, FL, FA = total land area (without inland water), Forest Fund, forest land, forested area, respectively; AGS = average growing stock (calculated for main forest species under state forest management).
Source: Goskomles, 1990b, 1991a.

The calculations carried out have tried to isolate the effects of management intervention on C sequestration by employing the following approach:

(total C storage with management intervention) - (total C storage without management intervention) = added C storage.

To estimate the potential increase of carbon sequestration that would result from improved management, the ecological, technological, and social particularities of Russia and Russian forests must be taken into account. A major problem in Russian forestry is forest fire protection. Consequently, any improvements in forest management in Russia must be linked with improvements in the forest fire protection system.

The temporal and spatial scales of ecological, technological, and social parameters place constraints on the availability of suitable land for plantations, reforestation, and other forestry operations in Russia. To determine realistic scenario measures for Russia, the concepts of "no-regrets" or "risk-averse" strategies have been followed (Miller *et al.*, 1990; Guchinsky and McKelvey, 1992). In addition, the following assumptions are built into the scenario:

- The direct costs of sequestering 1 t C should not exceed US$3 (1992 dollar value).
- Sufficient labor and technical equipment will be available.
- Relevant methods of forest management (including forest fire protection) will be implemented concurrency with the proposed reforestation.
- The period for realization of the identified options has been estimated to be 40 years, and the effects of the options are calculated for a 100-year period.
- Forest plantations that are necessary for local, regional, or sustainability reasons (watershed belts, reforestation of forest lands damaged by industrialization, forest-protection belts on agricultural land, etc.) are included in large-scale reforestation programs (LSR programs), even if these lead to a sequestration cost that exceed US$3 per ton of C.
- All measures that are normally required for the protection of the forests must be continued in combination with the new management options studied.
- All of the options must be simultaneously established in selected areas.

There are two basic uncertainties in the analyses. One is the very uncertain character of long-term forest forecasts in this case (difficulties in estimating the long-term economic and ecological development in Russia, and the uncertainties of the global change predictions and their direct and indirect impacts on forests). The second uncertainty is linked to the lack of required regional information and the lack of basic knowledge on different natural processes.

We evaluated the C dynamics in two scenarios:

- A "low" scenario based on the current state of forest management, wood utilization and wood processing. Risk functions on efficiency of the forest management were employed based on data from central European Russia. The C fixation under these conditions was estimated for the defined forest ecosystems.
- A "high" scenario based on a theoretically possible net C sink approach. This approach
  - uses the upper values of presented scenario parameters,
  - assumes that the wood removed from the forest would replace fossil fuels, and
  - uses no-risk functions on the efficiency of the forest management programs.

2. Reforestation of Forest Fund Land

2.1. MODEL

In the cases of afforestation of unforested lands, the accumulated C fixation function *F(ACA)* employed in the analyses is the typical function developed for even-aged stands (an example from such models is presented in *Figure 2*; Kurz *et al.*, 1992). We calculated *F(ACA)* according to the following scheme:

$$F(ACA) \;=\; R(t)\;\{S_{t*}(t)[f(S_pC)GS(t,S_p)F(FE)+Q(P)-F(DB)]\}\quad , \tag{1}$$

where $S_{t}*(t)$ is the area reforested in year t* [1 to 40]; *f(SpC)* is a function of species composition; GS(t,Sp) is a function of accumulated C in the growing stock of stemwood by time t and species S; *F(FE)* is a function for estimation of all carbon in any forest ecosystem; $F(FE) = TV(t,S_p)/GS(t,S_p)$; $TV(t,S_p)$ is the accumulated carbon fixation in the forest ecosystems as a whole; *Q(P)* is a function for removed forest products; *F(DB)* is a function for decomposition of phytomass left in the forest after thinning; and *R(t)* is a risk function.

F(ACA) gives the net C sink and is expressed in million tons of C by year t [1 to 100]; $R(t)$ $f(S_pC)$ $GS(t,S_p)$ $f(FE)$ describes the C accumulated in the forest ecosystems by year t (ton/ha). By summing *F(ACA)* for the periods *[0,t]*, t = 100, we get the total net C sink resulting from the afforestation carried out in the time frame of our scenario.

The coefficients employed for the C content in the analyses are 0.5 for oven dry wood and 0.45 in non-wood phytomass (Matthews, 1993).

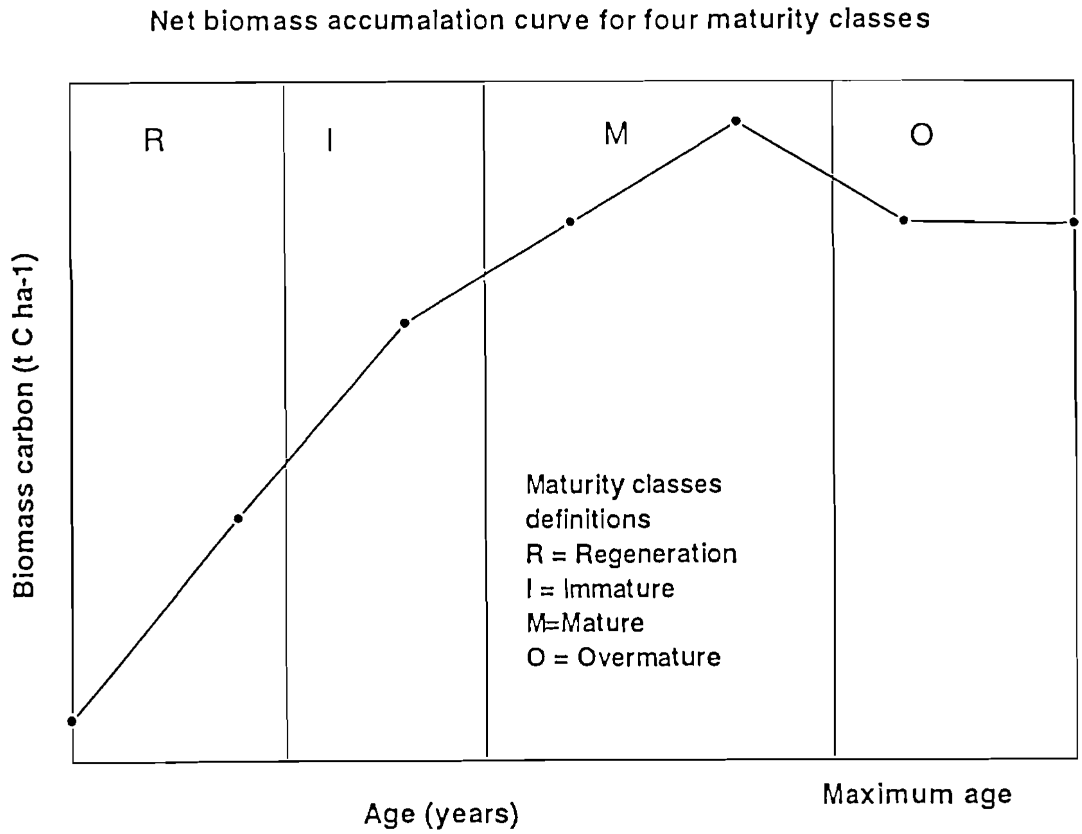

Figure 2. Dynamics of net biomass C accumulation. Source: Kurz *et al., 1992.*

2.2. POTENTIAL AREAS AVAILABLE FOR REFORESTATION

The Forest Fund of Russia is made up of areas covered by forests and areas not currently covered by forest but that could be used for future forestry production under certain conditions. The following information on the Russian forest fund was obtained from the Forest State Account of the former Soviet Union in January 1988 (Goskomles, 1990b, 1991a):

- 113 million ha of unforested areas are made up of sparse forests (60%), burned areas and dead stands (28%), glades (4%), and clear-cutting areas without sufficient regeneration (8%). More than 95% of these unforested areas are located in the Asian part of Russia.
- 298 million ha of so-called non-forest lands are made up of bogs (122 million ha) and unproductive land (90 million ha); the remaining 86 million ha are not considered in this study.

Totaling 411 million ha, the majority of these unforested and non-forest lands (368 million ha) are located in Siberia and Far Eastern Russia. Of these 368 million ha, 122 million ha are located in the current industrial harvesting zones and 246 million ha are in reserved (unused) areas.

Russian scientists previously estimated the area available for reforestation to be about 130 million ha in the former Soviet Union (Isaev, 1991a). In our opinion, this is an overestimate. All unforested areas in reserved forests, in naturally sparse forest areas (which constitute some 65% of the total sparse forest area), on sites of low productivity (site class V and lower), and in areas that are inaccessible because of economic conditions should be excluded from the estimates. We have also excluded 50% of the unforested areas disturbed by clear-cuts and 20% of the post-fire areas because probabilities of natural forest regeneration are good in these areas (Pisarenko, 1977; Pisarenko *et al.*, 1992; Goskomles, 1990a). On the other hand, we have added 15 million ha of non-forest wetland because of the possible application of melioration drainage (Vompersky *et al.*, 1975). Taking these assumptions into account, the available areas for reforestation of the unforested areas and non-forest lands have been estimated to be between 53 million ha and 75 million ha, with an average of some 64 million ha.

Areas disturbed by harvesting and fire are available for artificial reforestation. The areas of forest harvests in Russia are presented in *Table II.*

TABLE II.
Annual forest harvests in Russia, in 1,000 ha.

Form of harvest	1980	1985	1987	1989
Clear cuts	1,742	1,684	1,837	1,766
Other harvests	287	245	210	204
Total harvests	2,029	1,929	2,047	1,970

Source: Goskomstat, 1990.

The annual clear-cut area during the period from 1980 to 1990 was between 1.7 million and 1.8 million ha, mainly in the southern and middle taiga and to some extent in mixed forests. Additional annual disturbances in these zones were estimated to be about 0.2 million ha from forest fires and at least 0.1 million ha by other sources, such as pollutants and insect damage (All Russian Information and Research Center for Forest Resources, 1992). Therefore, the total annual disturbance of forested areas caused by mainly anthropogenic factors is at least 2 million ha in Russia. These figures are comparable with the reforestation figures in *Table III.*

To provide satisfactory regeneration, artificial reforestation is required in 30% of the middle and northern taiga, in 50% in the southern taiga, in 70% in the mixed forests, and in between 90% and 100% in forest steppe and steppe areas (Goskomles, 1990a).

TABLE III

Reforestation in state forests in Russia between 1970 and 1990, in 1,000 ha.

	1970	1980	1985	1989	1990
Artificial regeneration	724	820	719	599	566
Prepared for natural regeneration*	1,007	1,042	1,156	1,279	1,265
Total	1,731	1,862	1,875	1,878	1,831

*These measures include undergrowth protection, scarifying, removal of slash, establishment of seed trees, etc. The success rate of the regeneration attempts is unknown. Source: Goskomstat, 1990, 1991.

Due to the low quality of the artificial regeneration and the occurrence of forest fires, the survival rate of the plantations has been low in Russia. On average over the past 50 years, only about 60% of the artificial regenerations have been successful. Since 1945, 41.8 million ha have been planted in the former Soviet Union, but the Forest State Account considers only 23.8 million ha to be successful (Goskomles, 1990a, 1990b; and Pisarenko *et al.*, 1992). The regeneration efficiency of the areas prepared for natural coniferous regeneration has also been rather low. In the northern regions of the European part of the former Soviet Union, only 20% of the naturally regenerated coniferous forests are regarded as being successful. The corresponding figure for the northwest region is 46% (Goskomles, 1990b).

Based on this information, there is clearly an opportunity in Russia for at least an additional 0.5 to 0.6 million ha per year of plantations. Assuming the same rate of regeneration for our scenario over a 40-year period, we estimate an additional total area for artificial plantations of 20 million ha from areas disturbed by harvesting and fire.

2.3. PRODUCTIVITY BY FOREST PLANTATIONS AND ESTIMATED C SEQUESTRATION RATE

The distribution of the site indices for the main species in Russia is presented in *Table IV*. The weighted (by area) average productivity for major species is shown in *Table V*. In the calculations the average site indices for areas available for LSR programs have been employed. The production figures are based on model results presented by Shvidenko *et al.* (1987) and Strochinsky *et al.* (1992), and are calibrated against yield tables presented by Voinov (1986), Korjakin (1990), Moshkalev (1984), and Sagreev *et al.* (1992).

During the period from 1970 to 1980 the forest plantations in the former Soviet Union were more than 90% coniferous (Goskomles, 1990a). The species breakdown of the trees planted

TABLE IV

Average site indices by species and vegetational zone.

Zones	Average site indexes by longitude and species											
	41°-50° east longitude (European part)						71°-80° east longitude (West Siberia)					
	Pn	Sp	L	B	As	H	Pn	Sp	L	C	B	As
Northern taiga	5.0	4.9	3.9	4.0	4.2	-	4.0	4.6	5.2	4.9	4.3	3.8
Middle taiga	4.0	3.8	3.2	3.3	2.8	-	4.0	3.6	3.7	3.7	3.2	2.6
Southern taiga	3.4	2.3	1.7	3.2	2.2	3.2	4.1	3.5	3.0	4.2	2.9	2.5
Mixed forest	2.1	1.9	1.7	2.0	1.7	2.5	-	-	-	-	-	-
Deciduous forests and forest-steppe	1.8	1.6	1.2	2.4	1.8	3.0	2.8	2.6	3.0	3.2	2.6	2.5
	101°-110° east longitude (East Siberia)					131°-140° east longitude (Far East)						
	Pn	Sp	L	C	B	Pn	Sp	L	C	B	As	H
Northern taiga	-	-	5.9	-	-	4.9	4.2	5.9	-	5.0	4.8	-
Middle taiga	3.6	3.7	3.9	4.1	3.5	4.1	4.1	3.9	4.0	3.5	3.4	4.1
Southern taiga	3.5	4.0	3.5	3.8	3.5	3.7	3.6	3.5	3.2	2.9	2.9	3.5
Mixed forests	-	-	-	-	-	2.8	3.2	3.3	2.8	3.1	2.3	3.5
Deciduous forests and forest steppe	2.4	3.2	2.4	3.4	2.2	3.0	3.4	3.7	3.3	2.8	2.4	3.8

Site indices in Russia are determined by the average age and height of the stand. For example, in site index class III, the average height at 50 years corresponds to 18.5m, and at 100 years, to 21.5m. The site index system can be roughly divided into five classes, with class I as the best and class V as the worst (Anuchin, 1982). Thus, 5.0 refers to site class V.

Abbreviations: Pn = pine (mainly *Pinus silvestris*); Sp = spruce (mainly *Picea sibirica* and *Picea exelsa*); L = larch (*Larix sibirica* and *Larix dahuria*); C = cedar (*Pinus sibirica* and *Pinus karajensis*); B = birch; As = aspen; H = hard deciduous (oak, beech, etc.).

Source: Unpublished data of the All-Union Research Center of Forest Resources (Kusmitchev, 1991).

(as dominant species) between 1986 and 1989 is 45% spruce, 37% pine, 8% cedar (*Pinus sibirica* and *Pinus korajensis*), about 5% larch, 3% hard deciduous species (mainly oak), and 2% other species in Russia (Pisarenko *et al.*, 1992). Taking into account the geographical distribution of areas for plantation program, we estimated the overall species composition as being 35% pine, 40% spruce and fir, 12% larch, 8% Russian cedar, 3% hard deciduous and 2% soft deciduous species. These estimates were used to calculate the function *f(SpC)* [see function (1)]; for a 100-year time series, the calculation results in an average total production of stemwood of 548 m^3/ha and an average growing stock of 356 m^3/ha.

In order to calculate the average C fixation rates, the following assumptions were used:

TABLE V
Growing stock and mortality by major species (m^3/ha).

Species	Average site index	Growing stock, by age (years)					Accumulated dieback, by age (years)				
		20	40	60	80	100	20	40	60	80	100
Pine	3.5	45	133	211	264	317	15	52	104	171	211
Larch	3.5	55	138	210	264	309	8	37	70	102	136
Spruce	3.3	25	99	213	366	458	5	33	91	122	178
Cedar	3.5	24	91	193	293	353	4	23	54	82	117
Hard deciduous	3.0	49	128	214	283	330	11	34	68	105	135
Soft deciduous	2.8	43	92	165	212	240	12	40	85	114	146
Average	—	37	116	209	307	356	9	38	85	126	192
Dieback, (%)	—	—	—	—	—	—	20	25	29	29	35

1. The productivity of plantations during the first 80 years will be about one site class higher than the productivity of current stands (the production figures presented in *Table V)* if an optimal species composition is established (from an ecological point of view) and if appropriate planting and thinning methods are used. An increase of the productivity of one site class corresponds to a conversion factor of current productivity by roughly 1.35. Vompersky *et al.* (1975), Efremov (1985), Babikov *et al.* (1988), and Chindiaev (1988), among others, have shown productivity increases of at least 30% using the measures discussed above.

2. The function for the total ecosystem C fixation *TV(t,Sp)* is represented by

$$TV(t,Sp) = 1.4\,GS(t,Sp) + F_1(AF) + F_2(AL) + F_3(AWD) + F_4(ASH) \qquad (2)$$

where 1.4 is the estimate of the ratio of the whole tree volume to the stemwood (Voinov, 1986; Shvidenko *et al.*, 1987; Usoltsev, 1988; Sagreev *et al.*, 1992); *GS(t,Sp)* is a function of accumulated C in the growing stock of stemwood by time *t* and species *S*; $F_1(AF)$ is a function of the dynamic C storage in green parts (foliage, understory green layers); and $F_2(AL)$, $F_3(AWD)$, and $F_4(ASH)$ are dynamics of C storage in litter, woody detritus (dry stems, ground coarse detritus, and dry branches of living trees), and soil humus, respectively. These functions are based on inventory data, numerous Russian and Western publications for average estimates on the above mentioned species composition, and expert estimates for basic groups of forest types by vegetational zones (Smagin, 1963; 1969; Posdnjakov *et al.*, 1969; Kurnaev, 1973; Utkin, 1975; Mitrophanov, 1977; Stefin, 1981; Academy of Sciences, 1983; Atkin and Smirnova, 1983; Kononova, 1984; Posdnjakov, 1985; Kobak, 1988; Usoltsev, 1988; Bazilevich, 1993a and 1993b).

The average values for function (2) are presented in *Figure 3.* It should be pointed out that the data are considerably aggregated; part of the data consists of expert evaluations based on many different sources.

Data on soil humus dynamics at all stages of reforestation are particularly uncertain. Although there are publications reporting significant losses of soil humus accumulation due to harvesting in mountains (Gorshenin, 1974; Shumakov and Kuraev, 1983; Stefin, 1981), the conclusion for major areas of final harvesting and cultivation for planting in Russia is that there is more replacement of organics than there are increases in mineralization (Remezov and Pogrebniak, 1965; Orlov, 1994). As a rule, for the first 7 to 12 years after planting, no decrease of soil humus has been detected.

The rate of C accumulation after planting depends on many factors, including the previous type of land use, types of reforestation, species, etc. Numerous investigations show a significant increase of C accumulation on initially forestless lands (e.g., after agricultural cultivation) — from 30-40% to 80-300% over 30 to 80 years. For soils of other types of land use, specifically for final harvesting areas, the picture is not clear (Wilde, 1964; Boone *et al.*, 1988; Johnson, 1992). In undisturbed Russian cedar forests in the southern taiga, about 10% of the C content of the annual litter fall is decomposed into organic soil matter (some 0.2 t ha yr) and the rest is oxidized into the atmosphere (Chagina, 1970). Similar results have been

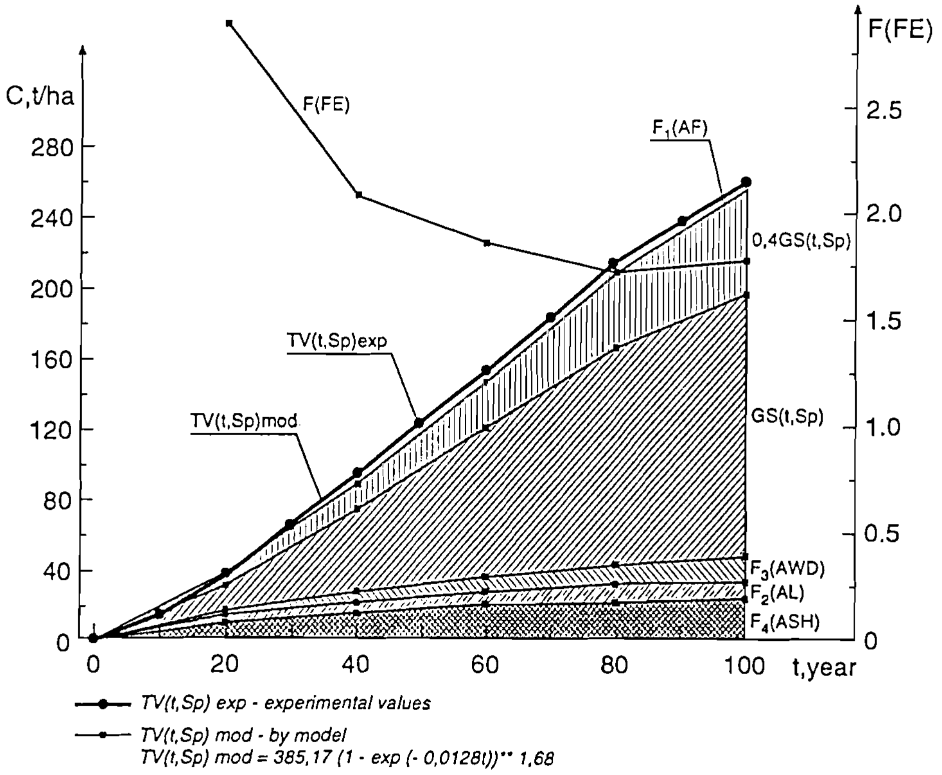

Figure 3. Average dynamics of additional carbon accumulation in forest plantations. Abbreviations of the functions are from equations (2), F(FE) is defined in equation (1).

reported for pine forests in southern Siberia (Orlovsky *et al.*, 1976). Our aggregated curves of soil humus and litter dynamics gave a C accumulation in humus of about 16% of the C accumulated in wood during a 100-year period. This is somewhat lower than was reported for other regions (Jenny, 1980; Birdsey, 1992; Sampson, 1992). The estimated accumulation of C in the wood detritus was relatively small, approximately 5% of the C accumulated in wood.

The total C accumulation in the forest ecosystems was approximated by a Mitscherlich growth function

$$TV(t,Sp) = 385.2*[1-\exp(-0.0128t)]^{1.68} \quad . \tag{3}$$

This results in 222.6 t C ha y^{-1} by the end of 100 years. Consequently, *F(FE)* is 2.67 for 20 years, and 1.76 for 100 years (*Figure 3*). Kauppi *et al.* (1992) used a partial *F(FE)* (the ratio between total phytomass and stemwood C) of 1.4 to 2.1 for the European forests; Sedjo (1992) estimated *F(FE)* for forests of the former Soviet Union to be 4.0. Generally, our estimates for intensively managed forest plantations are lower.

3. For the development of the plantations, we used the following probability risk function:

$$R(t) = R1(t)*R2(t) = \exp(-0.015t)*\exp(-0.010t) = \exp(-0.025t) \quad , \tag{4}$$

where *R1(t)* describes the probabilities for survival of forest plantations and *R2(t)* is the probability of reaching a certain growing stock by time *t*. The numerical data for a validation of the risk function were assumed to follow the 75% quartile for active-management forest plantations in Central Russia. Available statistical data on development of artificial reforestation are unacceptable due to insufficient quality of planting and protection of plantations in the past. The probability of reaching the results shown in *Figure 3* and calculated by function (4) is 0.86 by 60 years and 0.78 by 100 years.

Finally, in order to estimate the wood harvested by thinnings we used the production figures presented in *Table V* and estimated the thinning rate to be 35% of the total production during 100 years. Of the volume harvested in thinnings, some 75% is estimated to be used as raw material for forest industrial products (Bush and Yevin, 1984), with an average decomposition period of 10 years; the wood left in the forests (25% percent of the harvested wood plus a factor of 40% of all harvested wood representing the rest of the woody biomass) has a decomposition period of 20 years. Sensitivity analyses have been carried out concerning the effects of different lengths of decomposition periods on the overall results. The impact of decomposition periods ranging between 10 and 60 years was assessed and was found to have only a marginal impact on the overall results. The rate of decomposition has been described by simple exponential functions $y = exp\ (-kt)$, $T(0.95) = ln\ 20/k$, where $T(0.95)$ is the time required for the decomposition of 95% of the organic materials.

The plantation (reforestation) of unforested areas and non-forest lands (53 to 75 million ha with an average of 64 million ha) will generate a total additional C fixation of 9.8 Pg for the 100-year period studied, with a low estimate of the net sink of 6.0 Pg and a high estimate of the net sink of 14 Pg. From the source calculation for the reforestation of the 20 million ha of cut areas we achieve an additional total carbon fixation of 3.1 Pg for the period studied, with low and high estimates of the net sink of 2.1 and 4.4 Pg, respectively.

3. Reconstruction of Current Forests

3.1. APPROACH

An opinion held by Russian foresters in general is that the real productivity of forests in Russia is much below its potential due to insufficient land use, non-optimal species composition and age structure of stands, and large areas of secondary forests with low stock due to poor management. The relative average stocking in the European part of the former Soviet Union is 0.65 and is 0.54 for Siberia and the Far East (on a scale of 0 to 1.0); under current ecological conditions they should be in the range of between 0.80 and 0.85 (Antanaitis and Sagreev, 1981; Shvidenko *et al.*, 1987).

Model estimates of the potential productivity are of interest only as illustrations of the theoretical upper limit. Kulikova (1991) presents data on potential productivity of forests in the European part of the former Soviet Union based on the bioclimatological index (BCPI) (Shashko, 1967), which reflects an empirically received linkage between biological productivity and heat-water regimes for temperate and boreal zones,

$$BCPI = K_p \sum T / 1000 \quad ,$$

where K_p is a coefficient for the biological productivity depending on the ratio between heat and humidity and resulting water sufficiency under given temperature regimes; $\sum\ T$ is the sum of active temperature >10°C; *1,000* is the sum of active temperature for the southern boundary of forest tundra in European Russia. Data by Kulikova (1991) are given in *Table VI* as the ratio of potential production (growing stock) to actual production by major species.

Thus, for coniferous species, the theoretical production is estimated to be 1.8 to 2.0 times higher than the production actually achieved in the European part of the former Soviet Union. The corresponding figures for deciduous species are between 1.3 and 1.6. In estimates by

TABLE VI
Ratio of potential production to actual production by major species in the European part of the former Soviet Union.

Bioclimatological potential index (BCPI)	Pine	Spruce	Birch	Aspen	Oak
<0.8	2.6	3.1	2.0	-	-
0.8-1.2	2.8	2.7	1.9	1.1	-
1.2-1.6	2.6	2.3	1.5	1.5	-
1.6-2.0	1.9	2.1	1.4	1.3	1.3
2.0-2.4	1.8	2.0	1.3	1.3	1.9
2.4-2.8	1.7	1.9	1.2	1.2	1.8
>2.8	1.6	1.7	1.2	1.1	1.6

Gromov and Andajursky (1971) the differences are even higher (up to 2 to 3 times for forested areas).

To make a rough comparison of the forest productivity potentials of the European and Asian parts of Russia, the following simple climate index for forest growth was employed:

$$K = 0.01[R_t - (0.1T - 0.1T_r)] \quad ,$$

where T is the sum of temperatures greater than 10°C per day; R_t is the amount of precipitation evaporated at the temperature sum T; and T_r is the part of the temperature sum influencing the evaporation (Gorev, 1968). The average of this index, calculated by forest vegetational subzones (Kurnaev, 1973) is 1.7 for the European part of Russia and 1.2 for Siberia and the Far East. Total European forest land is equal to about one-third of the Asian forest land so, for Russia some 70% of the growth potential will be in the Asian part and about 30% will be in the European part (Kusmitchev, 1991).

Employing this simple approach results in a theoretical upper estimate for increased growth potential of 180 million m^3 yr^{-1} of stemwood for the European part of Russia and 420 million m^3 for the Asian part of Russia. This represents a C storage of some 210 million t C annually. It should be emphasized, however, that this is a theoretical calculation. The interesting question is how much of an area is really suitable and available for reconstruction of current forests.

We considered three possible options for improvement of the current forests, namely, replacement of low productive stands, partial replacement of "climax" stands, and reconstruction of soft deciduous forests. In principle, all three options include the same operations: reconstruction harvests (clear or selective cutting), reforestation (a combination of complete or partial artificial regeneration accompanied by natural regeneration of adequate species), and appropriate management. The net C sink *E(ACR)* in the low estimate can be calculated according to

$$E(ACR) = F(ACA) - L(CR) \quad ,$$

where *F(ACA)* is defined according to equation (1) with the additional assumption that no changes in soil humus occur during the period considered, and where *L(CR)* is an estimate of C losses in forest ecosystems due to decomposition of harvested wood. In the high estimate, additional C from removed wood as a fossil-fuel substitute was also added to equation (5).

3.2. REPLACEMENT OF STANDS WITH LOW STOCKING

The distribution of inadequately stocked stands (a relative stocking of 0.3 to 0.4) under stand forest management is presented in *Table VII*. Based on regional analyses of the areas relevant for replacement, we identified 48 million ha of site class IV and higher with a relative stocking of 0.3 to 0.4 and 12 million ha of site indices I to III with a relative stocking of 0.5. The accumulated C was estimated to be 6.7 Pg, or about 112 million t C year. Average removed growing stock (stemwood) has been calculated to be 60 m^3 ha, and the total woody mass has been calculated to be 84 m^3 ha (21 t C/ha). By dividing the harvest wood into two pools with a decomposition rate of 60 and 30 years respectively, we receive a net C sink in the low estimate of 3.98 Pg, and in the high estimate to 12.1 Pg, or 0.83 and 2.52 t C ha^{-1} $year^{-1}$, respectively. If the decomposition rates are changed to 40 and 20 years, respectively, there will be no changes in the results.

TABLE VII
Distribution of site indices for inadequately stocked forests (stocking fraction 0.3 to 0.4), in million ha.

Category of forests	Total Russia, site indices			Total	European Russia, site indices			Total
	≥2	3-4	≤5		≥2	3-4	≤5	
Coniferous	2.3	65.9	88.4	156.6	0.5	2.5	7.9	10.9
Hard deciduous	0.2	1.4	2.0	3.6	0.1	0.2	-	0.3
Soft deciduous	2.3	8.0	4.1	14.4	0.4	0.9	1.1	2.4
Total	4.8	75.3	94.5	174.6	1.0	3.6	9.0	13.6

Source: Goskomles, 1990b.

3.3. REHABILITATION OF "CLIMAX" STANDS

With this rather relative term "climax stands" we define mature and overmature stands that must be replaced because of sustainable forest management requirements. These stands are partially constituted by uneven-aged stands that are in an equilibrium state with equal mortality and growth rates. Large areas of such forests are situated mainly in protected areas and have been excluded from industrial exploitation by forest legislation, but replacement is required. The current forest inventory does not specifically identify these stands. Based on the forest inventory data (Goskomles, 1990b and 1991a), it can be concluded that there are 50 million ha of mature and overmature forests under protection (so called group I forests), 6.2 million ha of climax stands of *Betula ermani*, and 3.6 million ha of low productive hard deciduous forests. Other lands (e.g., some shrubbery areas) should also be included in this category. Thus, the total area is estimated to be at least 70 to 90 million ha. An essential part of these forests is located in mountain regions and on steep slopes, and is expected to be saved by current legislation and by rational landscape management. We have estimated the available areas for replacement to be some 20 million ha with an average growing stock of 70 m^3 of stemwood, 98 m^3 of woody mass, or about 28 t C ha. The additional C accumulated in the forest ecosystems by this replacement is estimated to be 2.2 Pg, with a low net sink estimate of 1.3 Pg and a high net sink estimate of 3.0 Pg.

3.4. REPLACEMENT OF SOFT DECIDUOUS STANDS

There are some 137 million ha of soft deciduous stands (birch, aspen, alder, willow, and poplar) in Russia and nearly 100 million ha of them are under state forest management. The majority of these stands are the result of forest fires and inefficient forest management. About 50% of these stands are represented by young and middle-aged stands (see *Table VIII*) and, as a rule, they grow on highly productive land that was previously occupied by coniferous species. The annual allowable cut (AAC) of soft deciduous species is about 210 million m^3 in all of Russia, of which 95 million m^3 are allocated to European Russia. The actual harvest of soft deciduous species was 74 million m^3 in 1980, 78 million m^3 in 1985, and 81 million m^3 in 1989 (Goskomstat, 1990).

The European-Ural zone is interesting, because as a result of concentrated clear cuttings and other anthropogenic and technogenic disturbances in this area, there are secondary birch, aspen, and alder forests growing on sites suited for spruce, spruce-fir and pine-spruce.

The areas of these forests are estimated to reach 70 to 80 million ha by year 2000 (Pismenov *et al.*, 1989). Natural transformation of these forests into coniferous forests will take about 250 years. As a rule, the current stands have a well-developed undergrowth of coniferous

TABLE VIII
Areas (million ha) and growing stock (billion m^3) of soft deciduous species in Russia under state forest management.

Species	Areas Type of Stands					Growing Stock	
	Total	Young	Middle-aged	Premature	Mature and overmature	Total	Mature and overmature
	Russia (total)						
Total	104.8	22.1	34.1	12.1	36.5	10.8	5.6
Birch	81.6	16.9	28.7	9.6	26.4	7.5	3.6
Aspen	16.9	4.4	2.9	1.6	8.0	2.5	1.8
	European Russia						
Total	37.3	9.1	14.5	4.2	9.5	4.3	1.6
Birch	27.3	6.5	11.7	2.9	6.2	2.8	0.9
Aspen	6.6	2.0	1.2	0.8	2.6	1.0	0.6

Source: Goskomles, 1990b, 1991a.

species (for about 70 to 90% of the areas). A specific concept for transformation of these forests into coniferous forests has been developed. This concept included selective cuttings of deciduous species, preservation of the coniferous undergrowth, and formation of relevant species composition and structure of stands by thinnings. The experiences show that high productive coniferous forests can be established in such a way.

The average lifetime of aspen stands in Russia is 50 to 80 years; the lifetime of a birch stand is 60 to 100 years (from an increment point of view). The vast majority of these stands are even-aged. Thus, after a 100 year growth period, the stands' C uptake is close to zero. We estimate that some 25 million ha of these forests ought to be replaced. The average growing stock to be removed is 70 m^3, which corresponds to 98 m^3 woody mass or 25 t C ha. The additional C sequestration by this replacement was calculated to be 2.7 Pg. The total C sink in the low estimate is 2.2 Pg and 5.1 Pg in the high estimate. The results of our estimates show that a reconstruction of the existing forests (all options considered in sections 3.1, 3.2, 3.3) may provide a C sink of some 75 million tons per year in the low scenario and 200 million tons per year in the high scenario.

4. Implementation of Appropriate Intermediate Stand Treatment

Intermediate treatment of stands (thinning and selective sanitary fellings) has been carried out on relatively limited areas in Russia (*Table IX*).

TABLE IX
Intermediate treatment of stands in Russia.

	1980	1985	1987	1989
Areas, mln. ha	2.4	2.6	2.5	2.3
Total harvest of wood, mln. m^3	32.8	36.2	37.9	37.3
Commercial wood,* mln. m^3	25.6	28.5	30.0	29.2
Industrial wood, mln. m^3	11.3	13.0	13.5	14.1

*Commercial wood = industrial wood (suitable for forest industrial production) + fuel wood + wood used by other industries, such as the chemical industry. Source: Goskomstat, 1990.

These actual harvest figures should be compared with the amount of thinning required to provide an acceptable level of forest management. The latest estimate by the USSR State Forest Committee (Isaev, 1991b) states that 10.4 million ha of stands less than 40 years old should be precommercially thinned annually and 19.0 million ha should be commercially thinned annually to meet the ecological requirements.

Isaev (1991b) estimates that to meet the ecological requirements, approximately 150 million ha^3 of commercial wood should have been harvested in 1990 in the form of intermediate treatments . He also estimates that in 1990 the ecological requirements on the total amount of selective sanitary fellings should have been about 715 million m^3 in Russia.

It is also of interest to compare the above-mentioned data with estimates on the total mortality in Russian forests. The current forest inventory does not provide data on natural mortality. Different estimates exist, but they are contradictory. Based on calculation by Kusmitchev (1991) and Sagreev (1993), and unpublished data by VNIIZlesresource and Lesproject (Shvidenko, 1991), we conclude that the natural mortality in the Russian forests ranges between 800 million and 900 million m^3 of stemwood per year. Such rates of mortality provide a strong argument for increased thinnings.

In the framework of our scenario we estimate the total area requiring regular thinning or selective sanitary fellings to be about 75 million ha, with an annual average harvest of about 6.0 to 6.5 million ha. The average removed volume has been calculated to be 20 m^3 per ha, or 5 t C ha^{-1}.

Georgievsky (1957) presented results that showed no evidence of increased productivity by the Russian forests due to increased thinning. Similar conclusions have been presented more recently by Bush and Yevin (1984) and by Sennov (1984). The general conclusion from yield experiments in Scandinavia is that thinning will not increase the total production in the stand but will increase the production of commercial volumes and decrease the natural mortality.

Schroeder (1991) has analyzed data from the literature and from forest growth and yield models to determine the impact of management on C storage. The forest management measures studied were thinning, fertilization, and control of competing vegetation. Schroeder concludes that thinning does not increase C storage and may actually cause a decrease. The only exception is thinning in very dense young stands. In Schroeder's analyses, the end use of the thinned volumes was not taken into account in the C balance calculations. Marland and Marland (1992) conclude, based on what they call a "simple model of C flows", that for forest with high standing biomass and low expected growth rates, the best option (with respect to C fixation) is to let the existing forest continue to grow. For areas with low stocks and modest expected growth rates, the best option is to provide forest management or to replace the forest. Cooper (1983) points out that thinning and intermediate harvest are intended to reduce natural mortality and concludes that thinning reduces storage of C somewhat, but the effects are not large if the thinning is done appropriately. The author also emphasizes that management of the forests for C fixation is quite different from management directed toward maximizing timber yield or financial return.

Nevertheless, this does not mean that intensive forest management and thinning are not of interest for the C fixation balance. Many indirect consequences are of vital importance, such as the provision of appropriate species composition, an increase in the production of valuable and long-lived forest products or to decrease the fire risks. In the low estimate approach we do not take into account any increase of productivity and additional C fixation by thinning. In the high estimate we calculated the total C sink to be 2.0 Pg in removed commercial wood and in raw material for energy production. If the thinning is not carried out, the actual thinning volume will die and decompose and emit CO_2 and small fractions of methane to the atmosphere.

5. Results and Discussions

A summary of the estimates discussed earlier in the text is presented in *Table X*. These estimates indicate a potential for a significant increase of C sequestration in Russian forests through the implementation of forest management measures directed toward an increase of forest productivity and improvement of the Forest Fund structure. The low estimate indicates an additional net C sink of about 165 million t C annually; and the corresponding figure for the high estimate is 425 million t C yr. The additional C fixation in forest ecosystems was estimated to be some 245 million t C yr, or about 0.4 t C annually for each of the approximately 650 million ha of forested areas (covered by main forest-forming species) in

TABLE X
Possible increase of C sequestration by improved forest management in Russia.

Measures	Area involved at the end of the 40-year scenario, in million ha	Annual rate, million ha	Additional C fixation, Pg	Total C sink, Pg, by version		Average C sink, t ha^{-1} $year^{-1}$, by version	
				Low	High	Low	High
Large-scale reforestation in unforested areas	64	1.6	9.8	6.9	14.0	1.3	2.7
Reforestation of burned areas	20	0.5	3.1	2.1	4.4	1.3	2.7
Reconstruction of low-stocked forests	60	1.5	6.7	4.0	12.1	0.8	2.5
Rehabilitation of "climax" stands	20	0.5	2.2	1.3	3.9	0.8	2.4
Replacement of soft deciduous stands	25	0.6	2.7	2.2	5.1	1.1	2.6
Implementation of appropriate intermediate stand treatments	75	6.0	-	-	3.0	-	5.0
Total	—	—	24.5	16.5	42.5	—	—

Russia. It should be pointed out that the C fixation rates employed in this study are lower than the fixation rates in most other large-scale studies (for an overview see Nilsson, 1993).

The low estimate of our scenario calculation probably must be considered as being closest to reality. Dixon *et al.* (1991) state that intensified silviculture management in the boreal zone could increase the carbon storage by about 17 t C ha on average (with a variation of 6 to 30 t C ha). There has been a strong increase in the C fixation in Nordic forests during the past 30 to 40 years. The increased C fixation is basically an effect of the increased growing stock, which is itself mainly an effect of rational forest management and silviculture (Lunnan *et al.*, 1991; Eriksson, 1991; MMM, 1992; Kanninen *et al.*, 1992; and Kauppi *et al.*, 1992).

It should also be pointed out that the results of this study are greatly dependent on the relevance of our scenario assumptions. There are several sources of uncertainties in our results; however they do not change the magnitude of the results or the general conclusions. More significant uncertainties are associated with the future political, legal, economic, administrative conditions in Russia. Although new forest legislation in Russia was approved in mid-1993, many legislative problems remain. There is no doubt, however, that forest management in Russian will remain under the control of federal or regional authorities and that forests will continue to be state property.

In spite of uncertainties in the calculations and the situation in Russia, there are clearly great opportunities for increased C sequestration through improved forest management. From an international perspective, there are some advantages to introducing such a program in Russia:

- The costs for land are low.
- There is technical and scientific knowledge and a work force is available in Russia.
- Russia has experience in reforestation programs.
- The total costs for a forestry C offset program in Russia seem to be competitive with plantation programs in other parts of the world (Nilsson, 1993).

APPENDIX 1
Russian Forest Classification

Forest Fund: Areas covered by forest and areas not covered by forests that nonetheless could be used for multiple forestry purposes.
Forest land: The Forest Fund is divided into non-forest land and forest land that is either covered by forests (called forested area) or temporarily not covered.
Forested area: Constituted of young stands with a density of 0.4 or more and other stands with a density of 0.3 or more.
Commercial forests: Forests in which final felling is accepted.

Forest Groups:

1. Protection, landscape, recreative forests, etc., where only partial cutting is allowed.
2. Multiple-use forests where clear cutting can be used but partial cutting is a common harvesting method.
3. Wood-production forests where clear cutting is the principal harvesting method.

Commercial wood: Includes industrial wood (volume given under bark) and fuelwood (volume given over bark).
Density or stocking: Determined as the ratio between the sum of the basal areas of the actual stand at breast height and sum of basal areas of a normal stand according to yield tables.
Site index: Productivity class determined by the mean height at a certain age. Two different indices were employed in the Soviet Union — one for coniferous and deciduous species with suckers origin and one for all other species and origin.
Hard deciduous species: Oak, beech, ash, hornbeam, maple, and hard birches.
Soft deciduous species: Poplar, aspen, and soft birches.
Coppice: Forest composed of stool-shoots or root seedlings.
Sparse stands: Young stands with a density lower than 0.4 or other stands with a density lower than 0.3.

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