

FEDERAL AGENCY OF FOREST MANAGEMENT
INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS

**TABLES AND MODELS OF GROWTH AND PRODUCTIVITY
OF FORESTS OF MAJOR FOREST FORMING SPECIES
OF NORTHERN EURASIA
(standard and reference materials)**

Second edition, supplemented

(Summary in English)

Tables and models of growth and productivity of forests of major forest forming species have been approved by the Federal Agency of Forest Management of Russia and recommended for use in forestry and forest management of Russia (Protocol of the Council of Federal Agency of Forest Management No 2 dated by 8 June 2006).

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Summary

This book includes four types of models and tables destined for use in forest inventory, for planning of forest management activities, for different scientific applications, and as cognitive and training materials for professional education in forestry and forest management: growth (yield) models and tables (M/T), M/T of biological productivity, general M/T of growth and mortality of stands of major forest forming species of Northern Eurasia, and “standard” tables of basal area and growing stock of fully-stocked stands. The information is available at http://www.iiasa.ac.at/Research/FOR/forest_cdrom/. The Federal Service of Forest Management of the Russian Federation has approved the tables and models included in this issue and recommended them for use in forestry and forest management of the country.

Growth (yield) models and tables (GMT)

Two types of growth models and tables (below - GMT) presented in this issue – for fully-stocked and modal stands - are widely used in Russian forestry and forest management. By definition, fully stocked stands are represented by the most productive (i.e., having maximal growing stock) forests, which potentially are able to grow under given growth conditions. GMT of such a type represent patterns, which should be formed by sustainable forest management. GMT of modal stands describe the growth of actual, existing forests and, thus, take into account the impacts of regional regimes of forest management and natural disturbances. General GMT comprise averaged data for the entire growing area of an individual (dominant) species, and regional ones - for an individual region. A total of 142 ecological regions within Russian territories were used as a primary unit of spatial distribution of GMT (Figure 6, English names of ecoregions are presented in Table below). Ecoregions were established based on the following major principles: (1) homogeneity of the territory by growth conditions (climate, soil); (2) similarity of major land forms (mountain versus plain areas); (3) specifics of hydrological regimes (e.g., presence of permafrost); (4) similarity of anthropogenic impacts on forests and level of forest transformation; and (5) belonging of individual ecoregions to the same administrative region (*subject of the Russian Federation*). The recommended regions for the use of GMT are indicated in the names of the corresponding regional GMT (see *Content* in English).

Site index was used as a major tool of classification of GMT by level of productivity. All GMT were set in a unified system of site indexes. The unification means that the same average heights were used at base ages for all GMT in order to denote site index classes. The base ages were: 50 years for fast-growing species, 160 for Siberian cedar - stone pine (*Pinus sibirica*) and 100 years for the rest of the major forest forming species. For these ages, the heights were taken from the general site index (bonitat) scale by Prof. M. Orlov (Table VI of introductory Chapter). Forest types (according to the Russian definition of this term) were used as a second classifier in regional models (e.g., separate models were developed for automorphic and hydromorphic growth conditions of the same species growing in the same region) but within the framework of the site index system.

Modeling and unification of GMT were provided due to the following reasons. (1) Many of the existing growth (yield) tables were established a long time ago (the first yield tables in Russia were published in 1844) and do not represent conditions of a rapidly changing environment. Northern Eurasia currently has a different climate than three decades ago. Different sources assess the increase in productivity of boreal forests to be about 1–4% per decade due to climate change, CO₂ fertilization and nitrogen deposition. It is practically impossible to redevelop hundreds of yield tables based on new environments and the only practical way (at least for Northern Eurasia) is to present existing yield tables in an analytical form as the basis for current and future relevant modeling corrections. The majority of yield tables which are used in Russia have been published in a tabular form and corresponding models are not known. (2) Analysis and synthesis of yield tables, particularly for the huge NE forest territory (900 million ha or about a quarter of the global forest area), has an obvious cognitive sense because they are based on the growth and productivity of forests during the “pre-global change” period, and it is important

to retain this information. (3) A unified system that would accumulate the regularities of growth and dynamics of forests is needed for the development of other diverse “semi-empirical” types of models, e.g., models of biological productivity.

From several hundreds of yield tables developed for Northern Eurasian forests, about 130 were included in the system (of which all are used in practical forestry or which are interesting from a historical or cognitive points of view) including different types of GMT - general and regional, for fully stocked and modal, naturally formed and planted, single-species and mixed stands.

The Richards–Chapman growth function was used as an analytical expression for the modeling within individual site indexes. The estimates of parameters were calculated by site indexes for one or several yield tables (if such tables were available for the same object should be modeled), and site indexes within individual species were aggregated by a polynomial quadratic form. The modeling results were considered satisfactory if the root-sum-square difference between the model and the initial (from yield tables) dynamics of basic indicators did not exceeded $\pm 3\%$, and in any individual point was less than $\pm 6\%$. The adequacy of the models was checked in the standard way by analyzing the residuals. The coefficients of the Richards–Chapman function substantially vary for different tree species and geographical locations but can be represented by a regression two-dimensional function which includes site index and relative stocking of stands for individual species and homogeneous site conditions (Shvidenko et al., 1995). A special modification of the growth function has been developed for natural forests of the taiga zone which have succession stages of over-mature forests of which basal area and growing stock decrease by age (Venevsky and Shvidenko, 1997).

Results of the modeling showed that the established analytical system of GMT satisfactorily represents specific features of growth of the Northern Eurasia’s boreal and temperate forests for diverse species, regions and sites. The accuracy of this transformation corresponded to the requirements were formulated above and was provided for about 96% of all compared values. Thus, the system has accumulated huge semi-empirical information collected by many generations of thousands of forest inventory professionals and scientists across Northern Eurasia (including in this region territories of the former Soviet Union) during the last 150 years. This information, which was dispersed in hundreds of not readily available Russian sources, is presented in the system in an explicit and “operational” form.

Development of models (tables) of biological productivity (MBP)

Models of biological productivity (MBP) represent dynamics of phytomass and NPP of forest ecosystems. The models have been developed in two steps: (1) development of models for estimation of phytomass’ dynamics, and (2) modeling of dynamics of Net Primary Production of forest ecosystems.

In order to assess dynamics of phytomass, the ratio R^i of phytomass fractions F to growing stock GS (i.e., Biomass Extension Factor) as a function of biometric characteristics of forests T_j (which are defined by forest inventory in Russia) were modeled, i.e.,

$$R^i = F / GS = f(T_j). \quad (1)$$

A database, which includes some 3500 sample plots and 250 regional studies, has been used for parametrizing R^i . The models have been presented in the form

$$R^i = c_0 \cdot SI^{C_1} \cdot A^{(C_2 + C_3 \cdot RS + C_4 \cdot RS^2)} \quad \text{and} \quad (2)$$

$$R^i = c_0 \cdot A^{C_1} \cdot SI^{C_2} \cdot RS^{C_3} \cdot \exp(C_4 \cdot A + C_5 \cdot RS) , \quad (3)$$

where A is age (years), SI is site index (coded as 3, 4, ..., 13 for I_c , I_b , ..., V_b site indexes, respectively), RS is relative stocking, and c_1 – c_5 are regression coefficients. Five fractions of phytomass of trees were considered: stem wood over bark, bark, wood of branches (over bark), foliage, and roots.

Equations similar to (2) and (3) were also used for quantifying phytomass of understory (shrubs and undergrowth) and green forest floor. In the latter models, the mass of phytomass fractions F were directly modeled instead of modeling the ratio R . Appendix 3 contains the coefficients of phytomass models. Equations (1) and (2) are adequate by independent and dependent variables for tree species and ecoregions involved in the analysis. These equations and, as a rule, regression coefficients are statistically significant at 0.05 level of significance.

In order to develop MBP, a special simulation algorithm which combines GMT, models of phytomass and a number of parameters describing biological production of forest ecosystem was developed. This algorithm was published (Швиденко и др., 2004; Shvidenko et al., 2007) and is briefly described in the introductory Chapter to this issue.

Russian classifications of forests by types of age structure of stands are based on variation coefficients of age and diameter of trees constituting a stand and usually include (1) even-aged and relatively even-aged stands, (2) relatively uneven-aged, (3) (absolutely) uneven-aged stands, and (4) gradually uneven-aged stands (Shvidenko et al., 2000; Semechkin, 2002). The major part of the models developed have been produced for single species and even-aged stands. For mixed stands, simplified models that represent the dynamics of species composition, average height and diameter of dominant species were developed. For such type of models, the dynamics of growing stock volume and total production (of stem wood) are presented altogether for all species. One can point out that the dynamics of these two latter indicators are accurately and adequately described by the Richards–Chapman equation that demonstrates the availability of aggregated regularities of the production process in mixed forests, at least in terms of increment/accumulation/mortality of stem wood. Satisfactory results of the modeling have also been achieved for relatively uneven-aged and gradually uneven-aged stands. For uneven-aged and gradually uneven stands, only some illustrative examples are presented.

In order to make all models compatible, the MBP were developed for all GMT included in the system discussed above. The analytical form of the MBP is bulky and is not presented in this issue. However, models presented in Appendixes contain enough information for compiling the algorithm for calculation of MBP. As an example, Figure 1 contains the graphical form of general MBP for fully-stocked pine forests.

The uncertainty of developed models is of a primary interest. Uncertainty of the initial yield tables cannot be estimated in any formal way. Assessment of the actual accuracy of the models of phytomass using traditional statistical methods is also difficult. The indicators of statistical accuracy of the equations should be used with some caution for a number of reasons: accuracy of initial data, which were collected during a long period of time, is mostly unknown; spatial distribution of sample plots does not correspond to the requirements of the designed experiment; there are differences in species composition of forests, in which phytomass is assessed, with those of forests in which experimental material was collected, etc. However, it has been shown that the developed system has an acceptable level of reliability. Using error propagation theory with a partial use of expert estimates and *a priori* probabilities, and standard sensitivity analysis, the total phytomass of Russian forests as a whole and for large regions can be estimated with the “summarized” error (i.e., a function of random and systematic errors, which cannot be separated for a majority of cases) in the range of 4 to 7% (*a priori* confidential probability 0.9), respectively, under the assumption that the entire system of accounting does not have unrecognized biases (Shvidenko et al., 2003, 2004). The application of the MBP to initial sample plots has shown that there are no systematic errors by major phytomass fractions. Some systematic differences are recognized for NPP (from +5 to +10% for some species and regions) that could be (at least, partially) connected to a changing environment. The development of models of biological productivity of the considered type presents, to our knowledge, the first attempt of such a kind for Northern Eurasian forests.

Tables and models of gross and net growth (TMG)

Tables and models of gross and net growth (TMG) are developed for stands of 5 forest forming species (pine, spruce, oak, birch and aspen). They contain age dynamics of gross (dTV) and net (dGS) growth and mortality (dM) by site indexes and relative stocking, averaged for the entire growth area of the above mentioned tree species.

The TMG have been developed based on regularities of dynamics of total production and growing stock volume under different densities using the approach suggested in (Кенставичюс и др., 1981). The models have been developed using non-linear dependence of growing stock and total production (total volume) of stands on relative stocking. Models of dynamics of growing stock and total production under different stocking have been presented by the Richards-Chapman growth function and further aggregated by the three-dimensional (site index, age and relative stocking) function. The models were parametrized based on available information from different publications (e.g., Кенставичюс и др., 1981; Тюрин и др., 1945; Загреев и др., 1992) and using regularities derived from growth models presented in this issue. Gross and net growth were calculated as numerical values of derivatives of the developed models, and mortality – as the difference between gross and net growth. Data presented in Part 3 represent a simplified and modified version of tables from Shvidenko *et al.*, 1996. It is relevant to point out that the TMG are developed for mechanical aggregates of stands and do not specifically account for previous history of growth and forest management of stands. Thus, the accuracy of the TMG is not high, at least in application to individual stands.

“Standard” tables of basal area and growing stock of fully-stocked stands

“Standard” tables of basal area (BA) and growing stock (GS) of fully-stocked stands contain dynamics of BA and GS as a function of average height of stands. They are produced based on corresponding models of growth of fully-stocked stands. Such a type of reference data is widely used in the practice of forest inventory in Russia.

“Standard” tables included in this book reflect regularities of the corresponding growth models of fully-stocked stands presented in Part I. We did not provide any modeling correction and regulating of results of direct calculations. Such corrections could be done by forest inventory enterprises using regional experimental data. Dependently upon methodologies were used for development of the corresponding models of growth, the “standard” tables either include site index (bonitat) of stands as an input to the tables or not.

In order to provide a possibility to use the models and tables of this issue for non-Russian speakers, the English content is presented at beginning of the book. The first tables of each species and type contain column headers in English. English definitions of major terms used are given below.

Major terms and definitions

Average diameter – root-sum-square average of diameters of trees of a stand (element of forest) measured at breast height, i.e., at 1.3 m from the soil surface (diameter of the average tree of a stand), cm.

Average height of a stand (element of forest) – height corresponding to average tree of a stand (i.e., tree with average diameter), m.

Average increment (average change of growing stock) – yearly change of growing stock of a stand, calculated for the full period of the stand’s growth, i.e. $Z_{VCP} = M_A/A$, where M_A – growing stock of a stand at age A.

Basal area – sum of area of cross sections of all living trees constituting a stand (element of forest) measured at breast height, $m^2 \cdot ha^{-1}$.

Bonitat (site index) – (dimensionless) indicator of productivity of forest stands; it is defined by average age and average height of a stand (*element of forest*); in Russia site indexes are denoted by Latin numbers Ia, I, II, ... Va, etc.

Net growth (current change of growing stock) – change of growing stock volume of a stand per time unit, as a rule for 1 year. Measured in $m^3 \cdot ha^{-1} \cdot year^{-1}$.

Growing stock volume – sum of volumes of all living trees of a stand; measured in $m^3 \cdot ha^{-1}$.

Gross growth (current increment by total productivity) – change of total production per time unit, as a rule for 1 year. Measured in $m^3 \cdot ha^{-1} \cdot year^{-1}$.

Modal stands – actual stands (a term of Russian forest inventory)

Net Ecosystem Production (NEP) – difference between Net Primary Production and Heterotrophic Respiration. Measured in units of dry matter per time unit ($t^3 \cdot ha^{-1} \cdot year^{-1}$) or carbon ($t \text{ C } ha^{-1} \cdot year^{-1}$).

Net Primary Production (NPP) – amount of organic matter fixed in plant tissues. NPP is defined as difference between Gross Primary Production (Gross Photosynthesis) and Autotrophic Respiration. Measured in units of dry matter per time unit ($t^3 \cdot ha^{-1} \cdot year^{-1}$) or carbon ($t \text{ C } ha^{-1} \cdot year^{-1}$).

Phytomass (Live biomass) (of a forest ecosystem) – amount of organic matter of living plants constituting the ecosystem. MBP of this issue include 7 fractions (components) of phytomass: stem wood (over bark), bark of stems, wood of branches (over bark), foliage, understorey (undergrowth and shrubs), and green forest floor. Measured in units of dry matter (usually $t \cdot ha^{-1}$) or carbon ($t \text{ C } ha^{-1}$).

Species composition – distribution of growing stock volume by tree species constituting a stand; is represented by a formula expressed as the distribution in percent. For example, 7P3B means that from 65% to 74% of growing stock is presented by pine, and from 25% to 34% - by spruce.

Stocking (relative) – ratio of basal area of an estimated stand to the basal area of the analogues fully-stocked stand (the latter is taken from growth table of fully-stocked (normal) stands).

Total productivity (of a stand) – sum of growing stock volume which has been produced by a forest stand during the entire period of a stand's life, i.e. the sum of growing stock volume at age A and sum of mortality for the period before A; measured in $m^3 \cdot ha^{-1}$.

Ecological regions (ecoregions)

Code of ecoregions*	Name of ecoregions	Subject of the Russian Federation
009	Caucasus mountain deciduous forests	Republics: Dagestan, Ingushetia, Kabardino-Balkaria, Karachaevo-Cherkessia, Severnaja Osetia -Alania, Chechnja
011	Altai mountain middle taiga	Altai kray and Republic Altai
012	Altai forest steppe	
013	Altai mountain southern taiga	
014	Altai mountain forest steppe	
031	Kuban' northern steppe	Krasnodar Kray and Republic Adygeja
032	Caucasus coastal mountain deciduous forests	
041	Taimir tundra	Krasnoyarsk Kray including Taimir and Evenkia autonomous okrugs, as well as Khakass Republic
042	Putorana-Anabar sparse taiga	
043	Putorana mountain northern taiga	
044	Tungusky middle taiga	
045	Angara Southern taiga	
046	Kansk-Achinsk forest steppe	

Code of ecoregions*	Name of ecoregions	Subject of the Russian Federation
047	Khakassia mountain Southern taiga	
048	Sajansky mountain middle taiga	
051	Samarga mountain Southern taiga	
052	Southern Sikhote-Alin mountain coniferous-broadleaves forests	Primorsky Kray
053	Near-Khankaisky forest steppe	Stavropol Kray
071	Stavropol northern steppe	
072	Vorcaucasus mountain deciduous forests	
081	Okhotsky mountain Northern taiga	Khabarovsk Kray and Evreiskaja autonomous oblast
082	Low Amur mountain middle taiga	
083	Near-Amur mountain Southern taiga	
084	Middle Sikhote-Alin mountain coniferous-broadleaves forests	
085	Birobidjan coniferous-broadleaves forests	
101	Zeja-Selemdja mountain middle taiga	Amur oblast
102	Middle Amur mountain Southern taiga	
103	Zeja-Bureja forest steppe	
111	White Sea-Novaja Zemlja arctic tundra	Arkhangelsk oblast
112	Nenetsky forest tundra	
113	Pechora-Mezen' Northern taiga	
114	Onega-Northernern Dvina middle taiga	
121	Asrtrakhan semi-desert	Astrakhan oblast
141	Belgorod forest steppe	Belgorod oblast
151	Brjansk deciduous forests	Brjansk oblast
171	Kljazma (Vladimir) mixed forests with dominance of coniferous	Vladimir oblast
181	Volgograd southern steppe	Volgograd oblast
191	Belojarsk-Velikiy Ustjug middle taiga	
192	Upper-Sukhona southern taiga	
201	Voronezh forest steppe	Voronezh oblast
221	Vetluga mixed forests with dominance of deciduous	
222	Pjana-Teshink deciduous forests	
241	Ivanovo mixed forests with dominance of coniferous	Ivanovo oblast
251	Katanga middle taiga	Irkutsk oblast and Ust-Ordynsky Burjatsky autonomous okrug
252	Vitim mountain middle taiga	
253	Angara-Lena southern taiga	
254	Angara forest steppe	
255	Sajan-Nearbaikal mountain middle taiga	
271	Kalinigrad mixed forests with dominance of coniferous	Kaliningrad oblast
281	Tver mixed forests with dominance of coniferous	Tver oblast
291	Kaluga mixed forests with dominance of deciduous	Kaluga oblast
301	Korjak mountain tundra	Korjaksky autonomous okrug
302	Western Kamchatka mountain forest tundra	Kamchatka oblast
303	Pacific mountain northern taiga	
304	Cental Kamchatka middle taiga	
305	Southern Kamchatka mountain meadow sparse forests	

Code of ecoregions*	Name of ecoregions	Subject of the Russian Federation
321	Tom'-Jaija southern taiga	Kemerovo oblast
322	Inja-Cuhnja mountain forest steppe	
323	Altai-Kuznetsk mountain southern taiga	
331	Kirov southern taiga	Kirov oblast
332	Southern Kirov mixed forests with dominance of coniferous	
341	Kostroma southern taiga	Kostroma oblast
342	Makar'ev mixed forests with dominance of coniferous	
361	Soksky forest steppe	Samara oblast
362	Samara southern steppe	
371	Kurgan forest steppe	Kurgan oblast
381	Kursk forest steppe	Kursk oblast
411	Leningrad southern taiga	Leningrad oblast
421	Lipezk forest steppe	Lipetsk oblast
441	Chukotka mountain tundra	Magadan oblast and Chukotsky autonomous okrug
442	Eastern Kolima mountain sparse taiga	
443	Jana mountain northern taiga	
461	Moscow mixed forests with dominance of coniferous	Moscow oblast
462	Behind-Oka deciduous forests	
471	Kola tundra	Murmansk oblast
472	Khibini-Kheiven forest tundra	
473	Kandalaksha mountain northern taiga	
491	Novgorod mixed forests with dominance of coniferous	Novgorod oblast
501	Tara-Shagonar southern taiga	Novosibirsk oblast
502	Barabinsky forest steppe	
521	Irtish southern taiga	Omsk oblast
522	Irtish forest steppe	
531	Bolshekinelsky forest steppe	Orenburg oblast
532	Orenburg northern steppe	
541	Orel deciduous forests	Orel oblast
561	Penza forest steppe	Penza oblast
571	Kama-Kosinsk middle taiga	Perm Kray
572	Perm-Kama southern taiga	
573	Buisk-Irensk mixed forests with dominance of coniferous	
574	Vishera-Kos'va mountain middle taiga	
581	Pskov mixed forests with dominance of coniferous	Pskov oblast
601	Rostov northern steppe	Rostov oblast
611	Rjazan' deciduous forests	Rjazan oblast
631	Khopersk-Medvediza forest steppe	Saratov oblast
632	Saratov northern steppe	
641	Middle-Sakhalin mountain middle taiga	Sakhalinskaja oblast
642	Southern Sakhalin mountain southern taiga	
651	Middle Ural mountain southern taiga	Sverdlovsk oblast
652	Pel'ma-Sos'va middle taiga	
653	Pizhma-Navda southern taiga	
661	Upper-Dnepr mixed forests with dominance of coniferous	Smolensk oblast
681	Tambov forest steppe	Tambov oblast
691	Ob'-Tim' middle taiga	Tomsk oblast

Code of ecoregions*	Name of ecoregions	Subject of the Russian Federation
692	Ket-Vasjugan southern taiga	
701	Tula deciduous forests	Tula oblast
711	Jamal-Gidan' tundra	Tjumen oblast and Jamal0-Nenetsky and Khanti-Mansiisky autonomous okrugs
712	Ob'-Taz sparse taiga	
713	Ob'-Irtish middle taiga	
714	Irtish-Tobol southern taiga	
715	Ishim forest steppe	
731	Ul'janovsk deciduous forests	Uljanovsk oblast
751	Zlatoust mountain southern taiga	Cheljabinsk oblast
752	Western Cheljabinsk forest steppe	
753	Near Ural northern steppe	
761	Shilka mountain middle taiga	Chita oblast
762	Argun' mountain forest steppe	
781	Jaroslavl' southern taiga	Jaroslavl oblast
782	Naro-Plescheevsk mixed forests with dominance of coniferous	
801	Bashkiria forest steppe	Republic Bashkortostan
802	Southern Ural mountain southern taiga	
811	Tunkin-Zabaikal'e mountain middle taiga	Republic Burjatia
812	Selenga mountain southern taiga	
851	Kalmikija semi-desert	Kalmik Republic
861	Karelia northern taiga	Republic Karelia
862	Onega-Ladoga middle taiga	
871	Usinsk-Jurakh forest tundra	Republic Komi
872	Middle Pechora northern taiga	
873	Sktivkar middle taiga	
874	Komi southern taiga	
881	Mariisky mixed forests with dominance of coniferous	Republic Mariy El
891	Mordovia deciduous forests	Republic Mordovia
921	Tataria mixed forests with dominance of deciduous	Republic Tatarstan
931	Tuva mountain forest steppe	Republic Tyva
932	Sajano-Tuva mountain southern taiga	
941	Chepzovsk southern taiga	Republic Udmurtia
942	Valsk mixed forests with dominance of coniferous	
971	Chuvashia deciduous forests	Chuvash Republic
981	Northern Yakutia tundra	Republic Sakha (Yakutia)
982	Jana-Indigirka sparse taiga	
983	Vilju-Sangarsk northern taiga	
984	Middle-Lena middle taiga	
985	Upper Lena mountain middle taiga	

* Indicated on the map of ecoregions.

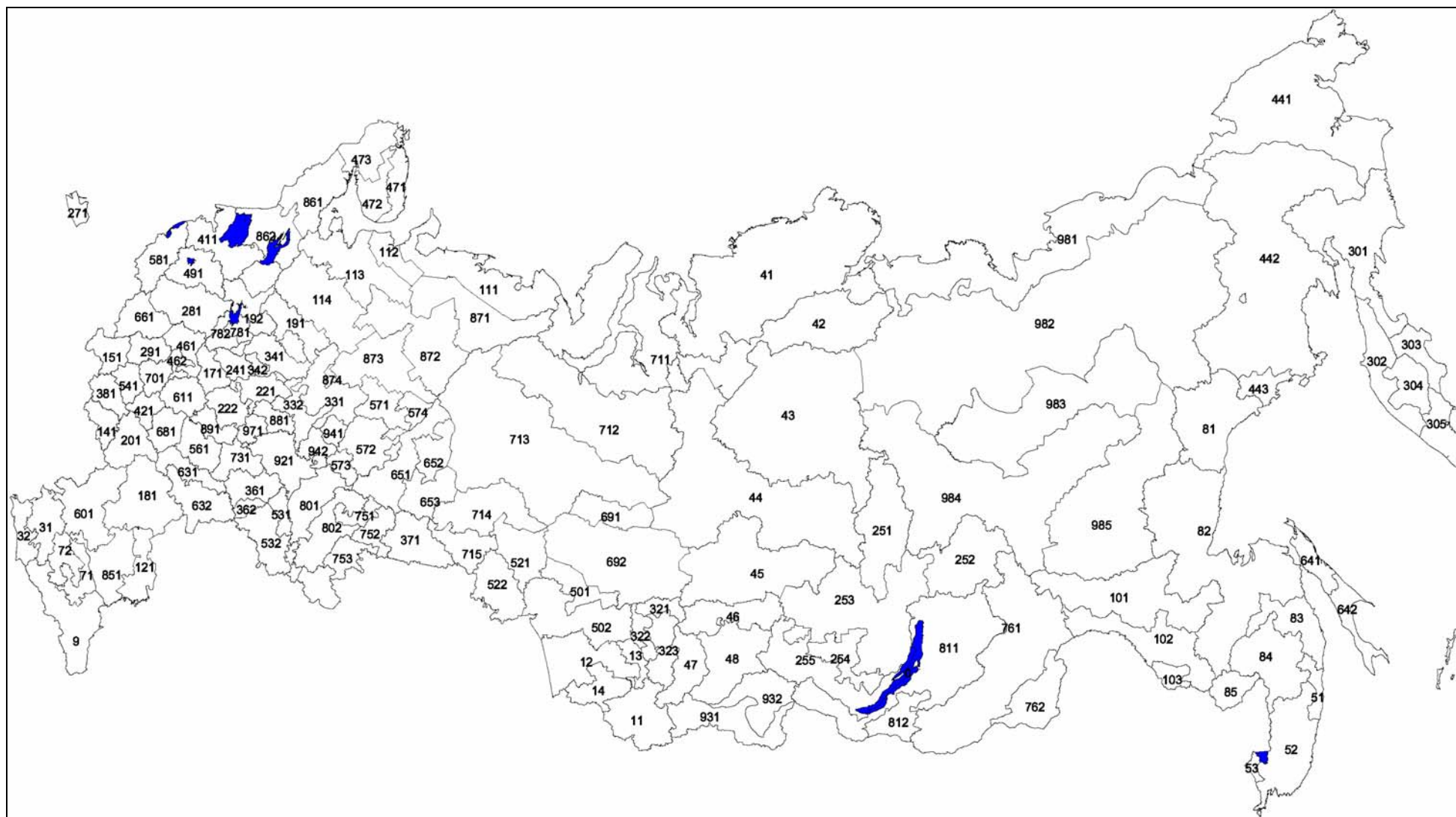


Fig. Ecoregions of Russia (*Shvidenko et al., 2000*).

Content

I. Foreword	28
II. Approach and methodological background	31
III. Sources of information used for modeling	52
IV. References	69
V. List of ecoregions	72
VI. Distribution of stands of seed and vegetative origin by site indexes	77
Part one. Growth tables	80
1. Growth of fully-stocked (normal) stands of Northern Eurasia – general tables	80
1.1. Growth of fully-stocked (normal) pine stands	81
1.2. Growth of fully-stocked (normal) spruce stands	85
1.3. Growth of fully-stocked (normal) fir stands	90
1.4. Growth of fully-stocked (normal) larch stands	92
1.5. Growth of fully-stocked (normal) stone pine (<i>Pinus sibirica</i>) stands	94
1.6. Growth of fully-stocked (normal) oak stands (<i>Quercus borealis</i>) of seed origin	99
1.7. Growth of fully-stocked (normal) oak stands (<i>Quercus borealis</i>) of vegetative origin	103
1.8. Growth of fully-stocked (normal) beech stands	105
1.9. Growth of fully-stocked (normal) ash (<i>Fraxinus excelsior</i>) stands	108
1.10. Growth of fully-stocked (normal) horn-beam stands	110
1.11. Growth of fully-stocked (normal) white acacia stands	112
1.12. Growth of fully-stocked (normal) ash (<i>Fraxinus manshurica</i>) stands	112
1.13. Growth of fully-stocked (normal) birch stands	115
1.14. Growth of fully-stocked (normal) aspen stands	117
1.15. Growth of fully-stocked (normal) lime-tree stands	121
1.16. Growth of fully-stocked (normal) gray alder stands	122
1.17. Growth of fully-stocked (normal) black alder stands	124
1.18. Growth of fully-stocked (normal) gray willow (<i>Salix alba</i>) stands	126
1.19. Growth of fully-stocked (normal) maple stands	128
2. Regional growth tables of pine stands	130
<i>2.1. Growth tables of fully-stocked stands</i>	130
2.1.1. Growth of fully-stocked pine stands in north-west ecoregions of the European part (zones of northern and middle taiga in territories of Karelia and Murmansk oblast')	130
2.1.2. Growth of fully-stocked pine stands in forest tundra and north taiga ecoregions of north-east of the European part	132
2.1.3. Growth of fully-stocked pine stands in middle taiga ecoregions of the European part	136
2.1.4. Growth of fully-stocked pine stands in mountain middle- and south taiga ecoregions of Urals	140
2.1.5. Growth of fully-stocked pine stands in middle taiga, south taiga, subtaiga and forest steppe ecoregions of Central and East Siberia	140
2.1.6. Growth of fully-stocked pine stands in south of West Siberia (subtaiga, forest steppe and mountain taiga ecoregions)	145
2.1.7. Growth of fully-stocked pine stands in north taiga ecoregions of West Siberia (hydromorphic forest types)	148
2.1.8. Growth of fully-stocked pine stands in mountain ecoregions of Zabaikalia	150
2.1.9. Growth of fully-stocked pine stands in small hill areas of Kazakhstan	152
2.1.10. Growth of fully-stocked belt pine stands in south of Siberia	155

2.1.11. Goal programs of growth of pine stands in the European part (ecoregions of zones of mixed forests, deciduous forests and forest steppe)	156
2.1.12. Growth of fully-stocked planted pine stands in the European part (ecoregions of zones of south taiga, mixed forests, deciduous forests, and forest steppe)	159
2.1.13. Growth of fully-stocked pine stands in Middle Povolzh'e (zones of mixed and deciduous forests and forest steppe)	161
2.1.14. Growth of fully-stocked pine stands in the European part (ecoregions of zone of mixed forests)	163
<i>2.2. Growth tables of modal stands</i>	166
2.2.1. Growth of modal pine stands in western ecoregions of the European part (zones of southern taiga, mixed and deciduous forests)	166
2.2.2. Growth of modal pine stands in Karelia and Murmansk oblast' (ecoregions of northern and middle taiga, relative stocking 0.65)	168
2.2.3. Growth of modal pine stands in Karelia and Murmansk oblast' (ecoregions of northern and middle, relative stocking 0.8)	169
2.2.4. Growth of modal pine stands in central ecoregions of the European part (southern taiga, zones of mixed and deciduous forests, forest steppe)	172
2.2.5. Growth of modal pine stands in forest tundra and northern taiga ecoregions of the European part	174
2.2.6. Growth of mixed modal pine stands in north taiga ecoregions of West Siberian plain	176
2.2.7. Growth of modal pine stands in hydromorphic forest types of taiga regions of Siberia	178
2.2.8. Growth of modal pine stands in authomorphic forest types of taiga regions of Siberia	180
2.2.9. Growth of modal planted pine stands in forest steppe and northern steppe ecoregions of the European part	183
3. Regional tables of fully-stocked spruce stands	185
<i>3.1. Growth tables of fully-stocked stands</i>	185
3.1.1. Growth of fully-stocked spruce stands of North-West European Russia (ecoregions of southern taiga and northern subzone of mixed forests)	185
3.1.2. Growth of even-aged fully-stocked spruce stands of northern and middle taiga ecoregions of European Russia	187
3.1.3. Growth of fully-stocked spruce stands of southern taiga ecoregions of the European part	190
3.1.4. Growth of fully-stocked spruce stands of southern taiga ecoregions of Ural	193
3.1.5. Growth of fully-stocked planted spruce stands of ecoregions of southern taiga, mixed and deciduous forests of the European part (goal programs of the growth)	196
3.1.6. Growth of fully-stocked spruce stands of ecoregions of the zones of mixed forests of the European part	198
3.1.7. Growth of fully-stocked stands of Shrenk's spruce (<i>Picea shrenkiana</i>)	200
3.1.8. Growth of uneven-aged fully-stocked spruce stands of European North	203
<i>3.2. Growth tables of modal stands</i>	206
3.2.1. Growth of modal spruce stands of North-West European Russia (ecoregions of southern taiga and northern subzone of mixed forests)	206
3.2.2. Growth of modal mixed spruce-deciduous stands of central part of the European part (ecoregions of southern taiga and mixed forests)	208
3.2.3. Growth of modal spruce stands of Middle Siberia (ecoregions of southern and middle taiga)	210
3.2.4. Growth of modal spruce stands of Northern Priokhotie (ecoregions of northern taiga)	212

4. Regional growth tables of larch stands	215
4.1. <i>Growth tables of fully-stocked stands</i>	215
4.1.1. Growth of planted fully-stocked larch stands in the European part (ecoregions of southern taiga, zones of mixed and deciduous forests and forest steppe)	215
4.1.2. Growth of fully-stocked larch stands in mountain taiga ecoregions of the south of West Siberia	216
4.1.3. Growth of fully-stocked larch stands in Central Siberia (ecoregions of middle and south taiga)	221
4.1.4. Growth of fully-stocked larch stands in forest steppe ecoregions of Burjatia and Irkutsk oblast'	224
4.1.5. Growth of fully-stocked larch stands in Magadan oblast' and east of Yakutia (Saha) Republic) (ecoregions of northern and sparse taiga)	227
4.1.6. Growth of fully-stocked larch stands in central and southern Yakutia (Saha) (ecoregions of mountain middle taiga)	229
4.1.7. Growth of fully-stocked larch stands in south of Far East (ecoregions of south taiga and coniferous-broadleaves forests)	230
4.1.8. Growth of larch stands of maximal productivity in Middle Siberia (ecoregions of middle and south taiga)	233
4.2. <i>Growth tables of modal stands</i>	236
4.2.1. Growth of modal larch forests of Yenisey Krjazh and south of Krasnoyarsk kray (ecoregions of mountain taiga forests and subtaiga)	236
4.2.2. Growth of modal larch forests of Angara River basin (ecoregions of middle and south taiga)	237
4.2.3. Growth of modal larch forests of Pribaikalie and upper reaches of Lena River (ecoregions of mountain taiga)	240
4.2.4. Growth of modal larch forests of taiga ecoregions of Zabaikalie (Republic Burjatia, Chita and Amur oblast')	242
4.2.5. Growth of modal larch forests of Central and North Yakutia (ecoregions of north, sparse and middle taiga)	244
4.2.6. Growth of modal larch forests of South Yakutia (Sakha) (forest types- Larch forests with bilberry, ecoregions of middle taiga)	245
4.2.7. Growth of modal larch forests of South Yakutia (Sakha) (forest types with <i>Ledum</i> and mosses, ecoregions of middle taiga)	247
4.2.8. Growth of modal larch forests of Magadan oblast' and North-East Yakutia (Sakha) (ecoregions of forest tundra and sparse taiga)	248
4.2.9. Growth of modal larch forests of South Far East (ecoregions of south taiga and coniferous-broadleaves forests)	250
4.2.10. Growth of modal larch forests of Priokhot'ja (hydromorphic forest types, ecoregions of northern taiga)	253
4.2.11. Growth of modal larch forests of North-East Yakutia (Sakha) dependently on soils and relief (ecoregions of forest tundra and sparse taiga)	254
5. Regional growth tables of fir stands	257
5.1. <i>Growth tables of fully-stocked stands</i>	257
5.1.1. Growth of fully-stocked fir stands (<i>Abies sibirica</i>) in south taiga ecoregions of West Siberia	257
5.1.2. Growth of fully-stocked fir stands (<i>Abies sibirica</i>) in mountain taiga ecoregions of Altai	259
5.1.3. Growth of fully-stocked fir stands (<i>Abies sibirica</i>) in south taiga ecoregions of Urals	262
5.1.4. Growth of fully-stocked fir stands (<i>Abies sibirica</i>) in Sakhalin	263
5.2. <i>Growth tables of modal stands</i>	266
5.2.1. Growth of modal fir stands (<i>Abies sibirica</i>) of mountain ecoregions of <i>Srednesibirskoe ploskogorie</i> (Middle Siberia table land)	266
5.2.2. Growth of modal fir stands (<i>Abies sibirica</i>) of mountain ecoregions of south Central Siberia	267

6. Regional growth tables of cedar (Stone pine, <i>Pinus sibirica</i>) stands	269
<i>6.1. Growth tables of fully-stocked stands</i>	269
6.1.1. Growth of fully-stocked cedar stands in mountain taiga ecoregions of Zabaikal'e (Republic Burjatia, Chita and Irkutsk oblast')	269
6.1.2. Growth of fully-stocked cedar stands in mountain taiga ecoregions of Mountain Altai	271
6.1.3. Growth of fully-stocked cedar stands in mountain taiga ecoregions of North and Middle Ural (authomorphic forest types)	274
6.1.4. Growth of fully-stocked cedar stands in mountain taiga ecoregions of North and Middle Ural (hydromorphic forest types)	276
6.1.5. Growth of fully-stocked relatively uneven-aged cedar stands in mountain taiga ecoregions of Mountain Altai	278
6.1.6. Growth of fully-stocked cedar stands in mountain taiga ecoregions of East Sajan	281
6.1.7. Growth of fully-stocked mixed cedar stands Middle Siberia table land (<i>Srednesibirskoe ploskogorie</i>)	282
<i>6.2. Growth tables of modal stands</i>	285
6.2.1. Growth of modal mixed cedar stands in Irkutsk oblast' (green mosses forest types)	285
6.2.2. Growth of modal mixed cedar stands in Irkutsk oblast' (hydromorphic forest types)	287
6.2.3. Growth of modal mixed cedar stands of Middle Siberia table land	289
6.2.4. Growth of modal cedar stands in Mountain Altai (group of forest types with <i>Bergenia</i>)	291
7. Regional growth tables of oak stands	294
<i>7.1. Growth tables of fully-stocked stands</i>	294
7.1.1. Goal programs of growth of optimal oak stands in the European part (ecoregions of zones of mixed forests, deciduous forests and forest steppe)	294
7.1.2. Growth of fully-stocked oak stands of North Caucasus (ecoregions of zones of deciduous forests and forest steppe)	296
7.1.3. Growth of fully-stocked oak (<i>Quercus petraea</i>) stands of South European part (ecoregions of zones of steppe and forest steppe)	298
7.1.4. Growth of fully-stocked oak stands of seed origin in the European part (ecoregions of zones of deciduous forests and forest steppe)	300
7.1.5. Growth of fully-stocked oak stands of vegetative origin in steppe ecoregions of South-East of the European part	302
7.1.6. Growth of fully-stocked oak stands in ecoregions of zone of mixed forests of the European part	304
7.1.7. Growth of fully-stocked oak stands of vegetative origin in forest steppe ecoregions of forest steppe of the European part	306
7.1.8. Growth of fully-stocked oak stands (<i>Quercus iberica</i>) in Northern Caucasus	308
<i>7.2. Growth tables of modal stands</i>	311
7.2.1. Growth of modal oak stands in the European part (ecoregions of zone of deciduous forests and forest steppe)	311
7.2.2. Growth of mixed modal oak-birch-aspens stands in the European part (ecoregions of zone of deciduous forests and forest steppe)	312
8. Regional growth tables of birch stands	315
<i>8.1. Growth tables of fully-stocked stands</i>	315
8.1.1. Growth of fully-stocked birch stands of North-East of the European part (ecoregions of zones of south taiga and mixed forests)	315
8.1.2. Goal program of growth of birch stands in the European part (ecoregions of zones of mixed forests, deciduous and forest steppe)	317

8.1.3. Growth of fully-stocked birch stands of South Zauralie (ecoregions of forest steppe and northern steppe)	320
8.1.4. Growth of fully-stocked birch stands of plain part of Middle Priuralie (ecoregions of zones of south taiga, middle taiga and northern subzone of mixed forests)	321
8.1.5. Growth of fully-stocked birch stands of North-East of mountain taiga ecoregions of Middle Urals	322
8.1.6. Growth of fully-stocked birch stands of North-East of the European part (ecoregions of zones of south taiga and mixed forests)	323
8.1.7. Growth of fully-stocked birch stands of steppe ecoregions of West Siberia	326
<i>8.2. Growth tables of modal stands</i>	329
8.2.1. Growth of modal birch stands in south and middle taiga ecoregions of Siberia	329
8.2.2. Growth of modal birch stands in forest steppe ecoregions of Siberia	331
8.2.3. Growth of modal birch stands in mountain taiga ecoregions of South Siberia	333
8.2.4. Growth of modal birch stands in mountain taiga regions of Pribaikalie	335
8.2.5. Growth of modal birch stands in the European part	336
9. Regional growth tables of aspen stands	341
<i>9.1. Growth tables of fully-stocked stands</i>	341
9.1.1. Growth of fully-stocked aspen stands of vegetative origin of the European part (ecoregions of southern taiga and zones of mixed and deciduous forests)	341
9.1.2. Growth of fully-stocked aspen stands of Zauralie and West Siberia (ecoregions of middle and southern taiga)	343
9.1.3. Growth of fully-stocked aspen stands of Central and East Siberia (ecoregions of middle and southern taiga)	345
9.1.4. Growth of fully-stocked aspen stands in ecoregions of forest steppe and steppe of Siberia and Kazakhstan	347
9.1.5. Growth of fully-stocked aspen stands in western part of the European part (ecoregions of zones of mixed and deciduous forests)	349
9.1.6. Growth of fully-stocked two layer aspen-spruce stands in the European part (ecoregions of north taiga)	351
9.1.7. Growth of fully-stocked two layer aspen-spruce stands in the European part (ecoregions of middle taiga)	357
<i>9.2. Growth tables of modal stands</i>	363
9.2.1. Growth of modal aspen stands in the European part (ecoregions of south taiga and mixed forests)	363
9.2.2. Growth of modal aspen stands in West Siberia (ecoregions of middle and south taiga)	364
9.2.3. Growth of modal aspen stands in forest steppe ecoregions of Siberia	366
9.2.4. Growth of modal aspen stands in mountain taiga ecoregions of South of West and Central Siberia	368
9.2.5. Growth of modal aspen stands in south taiga ecoregions of Central Siberia	370
10. Regional growth tables of lime-tree, poplar, alder and hornbeam stands	373
<i>10.1. Growth tables of fully-stocked stands</i>	373
10.1.1. Growth of fully-stocked of lime-tree stands of vegetative origin in the European part (ecoregions of zones of deciduous forests and forest steppe)	373
10.1.2. Growth of fully-stocked of hornbeam stands of vegetative origin in the European part (ecoregions of zones of deciduous forests and forest steppe)	375
10.1.3. Growth of fully-stocked of stands of black alder of vegetative origin in South-West of the European part (ecoregions of zones of mixed forests, deciduous forests and forest steppe)	377
<i>10.2. Growth tables of modal stands</i>	380

10.2.1. Growth of modal stands of poplar (<i>Populus lavrofolia</i>) in Republic Tuva	380
---	-----

Part two. Tables of biological productivity (TBP)	383
--	------------

1. General TBP of fully-stocked (normal) forests	384
---	------------

1.1. TBP of fully-stocked (normal) pine forests	384
1.2. TBP of fully-stocked (normal) spruce forests	389
1.3. TBP of fully-stocked (normal) fir forests	393
1.4. TBP of fully-stocked (normal) larch forests	395
1.5. TBP of fully-stocked (normal) stone pine (<i>Pinus sibirica</i>) forests	399
1.6. TBP of fully-stocked (normal) oak forests (<i>Quercus borealis</i>) of seed origin	403
1.7. TBP of fully-stocked (normal) oak forests (<i>Quercus borealis</i>) of vegetative origin	407
1.8. TBP of fully-stocked (normal) beech forests	410
1.9. TBP of fully-stocked (normal) ash (<i>Fraxinus excelsior</i>) forests	413
1.10. TBP of fully-stocked (normal) hornbeam forests	415
1.11. TBP of fully-stocked (normal) white acacia forests	417
1.12. TBP of fully-stocked (normal) ash (<i>Fraxinus manshurica</i>) forests	420
1.13. TBP of fully-stocked (normal) birch forests	422
1.14. TBP of fully-stocked (normal) aspen forests	426
1.15. TBP of fully-stocked (normal) lime-tree forests	429
1.16. TBP of fully-stocked (normal) gray alder forests	432
1.17. TBP of fully-stocked (normal) black alder forests	435
1.18. TBP of fully-stocked (normal) gray willow (<i>Salix alba</i>) forests	437
1.19. TBP of fully-stocked (normal) maple forests	439

2. Regional TBP of pine forests	442
--	------------

<i>2.1. TBP of fully-stocked forests</i>	442
--	-----

2.1.1. TBP of fully-stocked pine forests in north-west ecoregions of the European part (zones of northern and middle taiga in territories of Karelia and Murmansk oblast')	442
2.1.2. TBP of fully-stocked pine forests in forest tundra and north taiga ecoregions of north-east of the European part	445
2.1.3. TBP of fully-stocked pine forests in middle taiga ecoregions of the European part	449
2.1.4. TBP of fully-stocked pine forests in mountain middle- and south taiga ecoregions of Urals	453
2.1.5. TBP of fully-stocked pine forests in middle taiga, south taiga, subtaiga and forest steppe ecoregions of Central and East Siberia	455
2.1.6. TBP of fully-stocked pine forests in south of West Siberia (subtaiga, forest steppe and mountain taiga ecoregions)	458
2.1.7. TBP of fully-stocked pine forests in north taiga ecoregions of West Siberia (hydromorphic forest types)	460
2.1.8. TBP of fully-stocked pine forests in mountain ecoregions of Zabaikalia	463
2.1.9. TBP of fully-stocked pine forests in small hill areas of Kazakhstan	465
2.1.10. TBP of fully-stocked belt pine forests in south of Siberia	469
2.1.11. TBP for goal programs of growth of pine forests in the European part (ecoregions of zones of mixed forests, deciduous forests and forest steppe)	471
2.1.12. TBP of fully-stocked planted pine forests in the European part (ecoregions of zones of south taiga, mixed forests, deciduous forests, and forest steppe)	475
2.1.13. TBP of fully-stocked pine forests in Middle Povolzh'e (zones of mixed and deciduous forests and forest steppe)	479
2.1.14. TBP of fully-stocked pine forests in the European part (ecoregions of zone of mixed forests)	482

2.2. <i>TBP of modal forests</i>	486
2.2.1. TBP of modal pine forests in western ecoregions of the European part (zones of southern taiga, mixed and deciduous forests)	486
2.2.2. TBP of modal pine forests in Karelia and Murmansk oblast' (ecoregions of northern and middle taiga, relative stocking 0.65)	489
2.2.3. TBP of modal pine forests in Karelia and Murmansk oblast' (ecoregions of northern and middle, relative stocking 0.8)	491
2.2.4. TBP of modal pine forests in central ecoregions of the European part (southern taiga, zones of mixed and deciduous forests, forest steppe)	493
2.2.5. TBP of modal pine forests in forest tundra and northern taiga ecoregions of the European part	496
2.2.6. TBP of mixed modal pine forests in north taiga ecoregions of West Siberian plain	499
2.2.7. TBP of modal pine forests in hydromorphic forest types of taiga regions of Siberia	502
2.2.8. TBP of modal pine forests in authomorphic forest types of taiga regions of Siberia	504
2.2.9. TBP of modal planted pine forests in forest steppe and northern steppe ecoregions of the European part	506
3. Regional TBP of spruce forests	509
3.1. <i>TBP tables of fully-stocked forests</i>	509
3.1.1. TBP of fully-stocked spruce forests of North-West European Russia (ecoregions of southern taiga and northern subzone of mixed forests)	509
3.1.2. TBP of even-aged fully-stocked spruce forests of northern and middle taiga ecoregions of European Russia	512
3.1.3. TBP of fully-stocked spruce forests of southern taiga ecoregions of the European part	515
3.1.4. TBP of fully-stocked spruce forests of southern taiga ecoregions of Ural	518
3.1.5. TBP of fully-stocked planted spruce forests of ecoregions of southern taiga, mixed and deciduous forests of the European part (goal programs of the growth)	521
3.1.6. TBP of fully-stocked spruce forests of ecoregions of the zones of mixed forests of the European part	524
3.1.7. TBP of fully-stocked forests of Shrenk's spruce (<i>Picea shrenkiana</i>)	527
3.1.8. TBP of uneven-aged fully-stocked spruce forests of European North	531
3.2. <i>Growth tables of modal forests</i>	533
3.2.1. TBP of modal spruce forests of North-West European Russia (ecoregions of southern taiga and northern subzone of mixed forests)	533
3.2.2. TBP of modal mixed spruce-deciduous forests of central part of the European part (ecoregions of southern taiga and mixed forests)	537
3.2.3. TBP of modal spruce forests of Middle Siberia (ecoregions of southern and middle taiga)	540
3.2.4. TBP of modal spruce forests of Northern Priokhotie (ecoregions of northern taiga)	542
4. Regional TBP of larch forests	544
4.1. <i>TBP of fully-stocked forests</i>	544
4.1.1. TBP of planted fully-stocked larch forests in the European part (ecoregions of southern taiga, zones of mixed and deciduous forests and forest steppe)	544
4.1.2. TBP of fully-stocked larch forests in mountain taiga ecoregions of the south of West Siberia	547
4.1.3. TBP of fully-stocked larch forests in Central Siberia (ecoregions of middle and south taiga)	552
4.1.4. TBP of fully-stocked larch forests in forest steppe ecoregions of Burjatia and Irkutsk oblast'	555
4.1.5. TBP of fully-stocked larch forests in Magadan oblast' and east of Yakutia (Saha) Republic (ecoregions of northern and sparse taiga)	557
4.1.6. TBP of fully-stocked larch forests in central and southern Yakutia (Saha) (ecoregions of mountain middle taiga)	560

4.1.7. TBP of fully-stocked larch forests in south of Far East (ecoregions of south taiga and coniferous-broadleaves forests)	561
4.1.8. TBP of larch forests of maximal productivity in Middle Siberia (ecoregions of middle and south taiga)	564
4.2. TBP of modal forests	568
4.2.1. TBP of modal larch forests of Yenisey Krjazh and south of Krasnoyarsk kray (ecoregions of mountain taiga forests and subtaiga)	568
4.2.2. TBP of modal larch forests of Angara River basin (ecoregions of middle and south taiga)	569
4.2.3. TBP of modal larch forests of Pribaikalie and upper reaches of Lena River (ecoregions of mountain taiga)	572
4.2.4. TBP of modal larch forests of taiga ecoregions of Zabaikalie (Republic Burjatia, Chita and Amur oblast')	574
4.2.5. TBP of modal larch forests of Central and North Yakutia (ecoregions of north, sparse and middle taiga)	576
4.2.6. TBP of modal larch forests of South Yakutia (Sakha) (forest types- Larch forests with bilberry, ecoregions of middle taiga)	577
4.2.7. TBP of modal larch forests of South Yakutia (Sakha) (forest types with <i>Ledum</i> and mosses, ecoregions of middle taiga)	579
4.2.8. TBP of modal larch forests of Magadan oblast' and North-East Yakutia (Sakha) (ecoregions of forest tundra and sparse taiga)	581
4.2.9. TBP of modal larch forests of South Far East (ecoregions of south taiga and coniferous-broadleaves forests)	583
4.2.10. TBP of modal larch forests of Priokhot'ja (hydromorphic forest types, ecoregions of northern taiga)	586
4.2.11. TBP of modal larch forests of North-East Yakutia (Sakha) dependently on soils and relief (ecoregions of forest tundra and sparse taiga)	587
5. Regional TBP of fir forests	590
5.1. TBP of fully-stocked forests	590
5.1.1. TBP of fully-stocked fir forests (<i>Abies sibirica</i>) in south taiga ecoregions of West Siberia	590
5.1.2. TBP of fully-stocked fir forests (<i>Abies sibirica</i>) in mountain taiga ecoregions of Altai	594
5.1.3. TBP of fully-stocked fir forests (<i>Abies sibirica</i>) in south taiga ecoregions of Urals	596
5.1.4. TBP of fully-stocked relatively uneven-aged mixed fir forests (<i>Abies sachalinensis</i>) in Sakhalin oblast' (ecoregions of south and middle taiga)	598
5.2. Growth tables of modal forests	600
5.2.1. TBP of modal fir forests (<i>Abies sibirica</i>) of mountain ecoregions of <i>Srednesibirskoe ploskogorie</i> (Middle Siberia table land)	600
5.2.2. TBP of modal fir forests (<i>Abies sibirica</i>) of mountain ecoregions of south Central Siberia	601
6. Regional growth tables of cedar (Stone pine, <i>Pinus sibirica</i>) forests	603
6.1. Growth tables of fully-stocked forests	603
6.1.1. TBP of fully-stocked cedar forests in mountain taiga ecoregions of Zabaikal'e (Republic Burjatia, Chita and Irkutsk oblast')	603
6.1.2. TBP of fully-stocked cedar forests in mountain taiga ecoregions of Mountain Altai	606
6.1.3. TBP of fully-stocked cedar forests in mountain taiga ecoregions of North and Middle Ural (authomorphic forest types)	609
6.1.4. TBP of fully-stocked cedar forests in mountain taiga ecoregions of North and Middle Ural (hydromorphic forest types)	612
6.1.5. TBP of fully-stocked relatively uneven-aged cedar forests in mountain taiga ecoregions of Mountain Altai	614

6.1.6. TBP of fully-stocked cedar forests in mountain taiga ecoregions of East Sajan	617
6.1.7. TBP of fully-stocked mixed cedar forests Middle Siberia table land (<i>Srednesibirskoe ploskogorie</i>)	619
6.2. <i>Growth tables of modal forests</i>	622
6.2.1. TBP of modal mixed cedar forests in Irkutsk oblast' (green mosses forest types)	622
6.2.2. TBP of modal mixed cedar forests in Irkutsk oblast' (hydromorphic forest types)	624
6.2.3. TBP of modal mixed cedar forests of Middle Siberia table land	626
6.2.4. TBP of modal cedar forests in Mountain Altai (group of forest types with <i>Bergenia</i>)	629
7. Regional growth tables of oak forests	632
7.1. <i>TBP of fully-stocked forests</i>	632
7.1.1. TBP of goal programs of growth of optimal oak forests in the European part (ecoregions of zones of mixed forests, deciduous forests and forest steppe)	634
7.1.2. TBP of fully-stocked oak forests of North Caucasus (ecoregions of zones of deciduous forests and forest steppe)	635
7.1.3. TBP of fully-stocked oak (<i>Quercus petraea</i>) forests of South European part (ecoregions of zones of steppe and forest steppe)	638
7.1.4. TBP of fully-stocked oak forests of seed origin in the European part (ecoregions of zones of deciduous forests and forest steppe)	639
7.1.5. TBP of fully-stocked oak forests of vegetative origin in steppe ecoregions of South-East of the European part	641
7.1.6. TBP of fully-stocked oak forests in ecoregions of zone of mixed forests of the European part	644
7.1.7. TBP of fully-stocked oak forests of vegetative origin in forest steppe ecoregions of forest steppe of the European part	645
7.1.8. TBP of fully-stocked oak forests (<i>Quercus iberica</i>) in Northern Caucasus	648
7.2. <i>TBP tables of modal forests</i>	650
7.2.1. TBP of modal oak forests in the European part (ecoregions of zone of deciduous forests and forest steppe)	650
7.2.2. TBP of mixed modal oak-birch-aspen forests in the European part (ecoregions of zone of deciduous forests and forest steppe)	651
8. Regional TBP of birch forests	654
8.1. <i>TBP of fully-stocked forests</i>	654
8.1.1. TBP of fully-stocked birch forests of North-East of the European part (ecoregions of zones of south taiga and mixed forests)	654
8.1.2. TBP of goal program of growth of birch forests in the European part (ecoregions of zones of mixed forests, deciduous and forest steppe)	657
8.1.3. TBP of fully-stocked birch forests of South Zauralie (ecoregions of forest steppe and northern steppe)	661
8.1.4. TBP of fully-stocked birch forests of plain part of Middle Priuralie (ecoregions of zones of south taiga, middle taiga and northern subzone of mixed forests)	663
8.1.5. TBP of fully-stocked birch forests of North-East of mountain taiga ecoregions of Middle Urals	665
8.1.6. TBP of fully-stocked birch forests of North-East of the European part (ecoregions of zones of south taiga and mixed forests)	667
8.1.7. TBP of fully-stocked birch forests of steppe ecoregions of West Siberia	670
8.2. <i>TBP of modal forests</i>	673
8.2.1. TBP of modal birch forests in south and middle taiga ecoregions of Siberia	673
8.2.2. TBP of modal birch forests in forest steppe ecoregions of Siberia	676
8.2.3. TBP of modal birch forests in mountain taiga ecoregions of South Siberia	679

8.2.4. TBP of modal birch forests in mountain taiga regions of Pribaikalie	681
8.2.5. TBP of modal birch forests in the European part	683
9. Regional TBP of aspen forests	687
<i>9.1. TBP of fully-stocked forests</i>	687
9.1.1. TBP of fully-stocked aspen forests of vegetative origin of the European part (ecoregions of southern taiga and zones of mixed and deciduous forests)	687
9.1.2. TBP of fully-stocked aspen forests of Zauralie and West Siberia (ecoregions of middle and southern taiga)	691
9.1.3. TBP of fully-stocked aspen forests of Central and East Siberia (ecoregions of middle and southern taiga)	694
9.1.4. TBP of fully-stocked aspen forests in ecoregions of forest steppe and steppe of Siberia and Kazakhstan	697
9.1.5. TBP of fully-stocked aspen forests in western part of the European part (ecoregions of zones of mixed and deciduous forests)	701
9.1.6. TBP of fully-stocked two layer aspen-spruce forests in the European part (ecoregions of north taiga)	703
9.1.7. TBP of fully-stocked two layer aspen-spruce forests in the European part (ecoregions of middle taiga)	708
<i>9.2. TBP of modal forests</i>	712
9.2.1. TBP of modal aspen forests in the European part (ecoregions of south taiga and mixed forests)	712
9.2.2. TBP of modal aspen forests in West Siberia (ecoregions of middle and south taiga)	715
9.2.3. TBP of modal aspen forests in forest steppe ecoregions of Siberia	717
9.2.4. TBP of modal aspen forests in mountain taiga ecoregions of South of West and Central Siberia	719
9.2.5. TBP of modal aspen forests in south taiga ecoregions of Central Siberia	721
10. Regional TBP of lime-tree, poplar, alder and hornbeam forests	723
<i>10.1. TBP tables of fully-stocked forests</i>	723
10.1.1. TBP of fully-stocked of lime-tree forests of vegetative origin in the European part (ecoregions of zones of deciduous forests and forest steppe)	723
10.1.2. TBP of fully-stocked of hornbeam forests of vegetative origin in the European part (ecoregions of zones of deciduous forests and forest steppe)	726
10.1.3. TBP of fully-stocked of forests of black alder of vegetative origin in South-West of the European part (ecoregions of zones of mixed forests, deciduous forests and forest steppe)	728
<i>10.2. TBP of modal forests</i>	730
10.2.1. TBP of modal forests of poplar (<i>Populus lavrofolia</i>) in Republic Tuva	730
Part three. General tables of growth and mortality of stands of major forest forming species of different stocking	732
<i>3.1. Pine stands</i>	733
3.1.1. Gross growth of pine stands	733
3.1.2. Net growth of pine stands	734
3.1.3. Mortality of pine stands	736
<i>3.2. Spruce stands</i>	738
3.2.1. Gross growth of spruce stands	738
3.2.2. Net growth of spruce stands	740
3.2.3. Mortality of spruce stands	742

3.3. <i>Oak stands</i>	744
3.3.1. Gross growth of oak stands	744
3.3.2. Net growth of oak stands	745
3.3.3. Mortality of oak stands	746
3.4. <i>Birch stands</i>	748
3.4.1. Gross growth of birch stands	748
3.4.2. Net growth of birch stands	749
3.4.3. Mortality of birch stands	750
3.5. <i>Aspen stands</i>	751
3.5.1. Gross growth of aspen stands	751
3.5.2. Net growth of aspen stands	751
3.5.3. Mortality of aspen stands	752

Part four. «Standard tables» of basal area and growing stock of fully-stocked stands of Northern Eurasia **754**

1. <i>Standart tables of basal area of fully-stocked stands</i>	755
1.1. Standart tables of basal area of fully-stocked stands – general tables	755
1.2. Standart tables of basal area of pine stands	763
1.3. Standart tables of basal area of spruce stands	771
1.4. Standart tables of basal area of larch stands	774
1.5. Standart tables of basal area of fir stands	778
1.6. Standart tables of basal area of cedar (Stone pine, <i>Pinus Sibirica</i>) stands	780
1.7. Standart tables of basal area of oak stands	783
1.8. Standart tables of basal area of birch stands	785
1.9. Standart tables of basal area of aspen stands	788
1.10. Standart tables of basal area of lime-tree, hornbeam and black alder stands	792
2. <i>Standart tables of growing stock of fully stocked stands</i>	793
2.1. Standart tables of growing stock of fully-stocked stands – general tables	793
2.2. Standart tables of growing stock of pine stands	802
2.3. Standart tables of growing stock of spruce stands	808
2.4. Standart tables of growing stock of larch stands	811
2.5. Standart tables of growing stock of fir stands	814
2.6. Standart tables of growing stock of cedar (Stone pine, <i>Pinus Sibirica</i>) stands	816
2.7. Standart tables of growing stock of oak stands	819
2.8. Standart tables of growing stock of birch stands	821
2.9. Standart tables of growing stock of aspen stands	824
2.10. Standart tables of growing stock of lime-tree, hornbeam and black alder stands	828

Appendices **829**

Appendix 1. Coefficients of models of growth of fully-stocked stands by species (general tables)	830
Appendix 2. Coefficients of regional growth models by species	835
Appendix 3. Coefficients of models for assessment of phytomass	872
Appendix 4. Coefficients of models of growth and mortality under different stocking	876
Summary (in English)	879
List of ecoregions (in English)	883