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 fooly-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, CO_2 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 ±3%, and in any individual point was less than ±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^i 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.,

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

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

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

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

where A is age (years), SI is site index (coded as 3, 4, …, 13 for Ic, Ib, …, Vb 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^i were directly modeled instead of modeling the ratio R^i. 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-Chapmen 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 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 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 Authotrophic Respiration. Measured in units of dry matter per time unit ($t^3 \cdot ha^{-1} \cdot year^{-1}$) or carbon (t 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 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	Tungussky 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	Primorsky Kray
052	Southern Sikhote-Alin mountain coniferous-broadleaves forests	
053	Near-Khankaisky forest steppe	
071	Stavropol northern steppe	Stavropol Kray
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	Rjasan 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	Siktivkar 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 Jakutia tundra	Republic Sakha (Jakutia)
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.

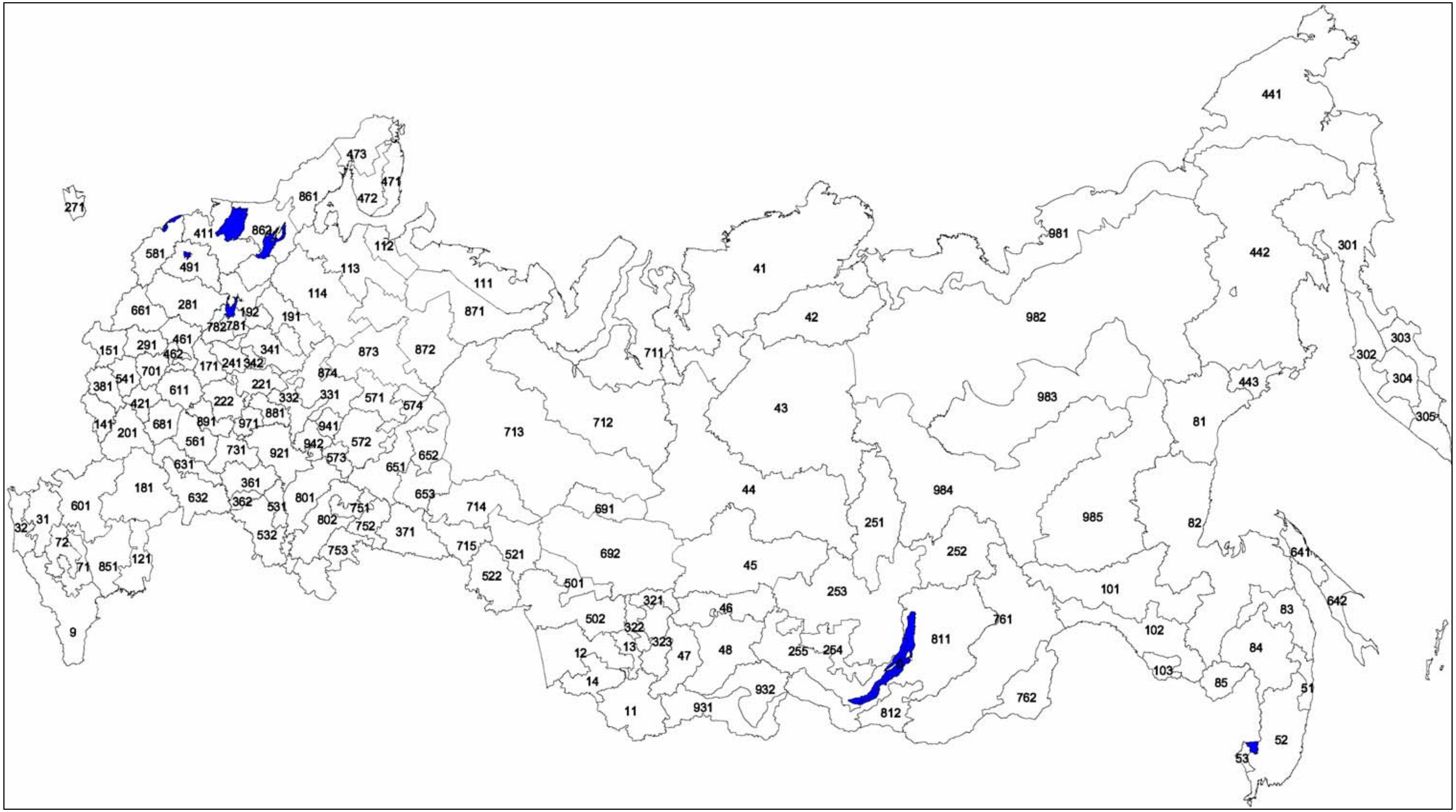

Fig. Ecoregions of Russia *(Shvidenko et al., 2000).*

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