http://www.balticforestry.mi.lt
ISSN 1392-1355
eISSN 2029-9230

Baltic Forestry 2021 27(1): 466
Category: review paper
https://doi.org/10.46490/BF466

Development of ideas within the framework of the genetic approach to the classification of forest types

VALERY FOMIN [1,2]*, ANNA MIKHAILOVICH [3], SERGEY ZALESOV [1], ARTEM POPOV [1] AND GENNADIY TEREKHOV [4]

[1] *Institute of Forest and Natural Resource Management, Ural State Forest Engineering University, 620100, Sibirskiy Trakt 37, Yekaterinburg, Russian Federation*
[2] *Institute of Plant and Animal Ecology of the Ural Branch of the Russian Academy of Sciences, 8 Marta Street 202, Yekaterinburg, Russian Federation*
[3] *Institute of Physics and Technology, Ural Federal University, 620002, Mira Street 19, Yekaterinburg, Russian Federation*
[4] *Botanical Garden, the Ural Branch of the Russian Academy of Sciences, 620144, 8 Marta Street 202a, Yekaterinburg, Russian Federation*

** Corresponding author: fomval@gmail.com, phone: +79022723408*

Fomin, V., Mikhailovich, A., Zalesov, S., Popov, A. and Terekhov, G. 2021. Development of ideas within the framework of the genetic approach to the classification of forest types. *Baltic Forestry* 27(1): article id 466. https://doi.org/10.46490/BF466.

Received 14 February 2020 **Revised** 28 December 2020 **Accepted** 18 January 2021

Abstract

This paper presents an analysis of achievements and the current state of one of the main trends of forest typological studies in the Russian Federation, namely, the genetic approach to the classification of forest types. The theoretical foundations of genetic typologies developed by the founders of this approach are described. The paper explains the relationship between the concepts of the forest-forming process and forest types. Also, a detailed description of the concept of forest-forming epochs according to the degree and depth of human impact on forests, as well as the forms and technical means of this impact, with examples of the practical use of genetic typologies in forest engineering and management are included. The paper provides an analysis of the main directions of development and improvement of genetic typologies, considering human-induced impacts at different levels and strengths, climate change, and the use of new technologies to reveal the potential of the genetic approach to the classification of forest types.

Keywords: forest typology, genetic approach, current state, prospects

Introduction

In the 20th century, several major scientific research areas in the field of forest typology were formed in Russia: the ecological or ecological-silvicultural classification by Alekseev–Pogrebnyak; Sukachev's phytocoenotic classification; the genetic classification proposed by Ivashkevich and Kolesnikov; and the dynamic classification developed by Melekhov (Pogrebnyak 1955, Sukachev 1957, Kolesnikov 1961, Melekhov 1961, Pogrebnyak 1968, Sukachev 1972, Kolesnikov 1974, Smolonogov 1998, Fomin et al. 2017). The first two abovementioned typologies are considered as natural ones (in Russia), and the latter two are defined as genetic typologies. The type of forest in natural classifications is considered from the aspect of homogeneous characteristics of forest biogeocoenosis (forest ecosystem) components. There are areas of homogeneous complexes of forest biogeocoenosis components, which are united into a forest type, i.e., criteria for the homogeneity of forest areas are used as the basis for determining the type of forest. In genetic classifications, the priority of the criteria for the spatial homogeneity of forest areas, when referring to the same forest type, has been replaced by criteria for homogeneity of the series of forest biogeocoenoses types over time (Fomin et al. 2017). In genetic classifications priority is given to homogeneity by origin (genesis), development processes and dynamics of forests in comparison with their homogeneity in composition and structure (Kolesnikov 1974). Each range of biogeocoenosis types refers to a specific forest type in the genetic classification.

Application of the “genetic” term to forest typology was very actively discussed in domestic research publications related to the development of genetic typologies for different regions of the former Soviet Union (fSU). For example, Sukachev shared the approach to vegetation genesis with authors of a genetic approach to the classification of forest types but noted that at the level of biogeocoenosis there is no transmission of hereditary information (Manko 2013). Nevertheless, the use of term "genetic" regarding the approach based on the classification of forest types described in the paper is appropriate, since the genesis studies of biogeocoenoses are based upon analysis of their populations, including genetic analysis that is the subject of prospective studies. That is why the founders of genetic approach to classification of forest types categorically refused to change name of their approach, e.g., to "dynamic".

Genetic classifications are always strictly regional and can be applied only within the areas with homogeneous climatic, orographic, soil and hydrological conditions. This is another fundamental difference between genetic and natural forest typologies. The latter have no strictly fixed regional limits for their usage (Kolesnikov et al. 1974). To emphasize the regional specificity of genetic classifications, they are often referred to as geographical genetic.

The ideas of Boris Ivashkevich, the founder of the genetic approach to forest type classifications, were further developed by his follower Boris Kolesnikov. Later, this approach was widely supported by forest scientists in the fSU. Since the 1950s, there has been an intense developing of genetic classifications and implementations of them into the practice of forest inventory and management in different regions of the fSU and in the Russian Federation as well.

Despite the great achievements in the field of developing forest type classifications in the fSU and Russian Federation using the genetic approach, there are still no detailed descriptions of these classifications in the international scholarly literature. Existing publications do not allow readers to understand practical implementation of the genetic forest typology. The objectives of this paper are threefold: 1) to provide a detailed review of a genetic approach to forest type classification, including practical aspects of its implementation; 2) to perform comparative analysis of genetic approach with related concepts developed by researchers from other countries; and 3) to formulate the main directions for development of genetic classifications in the future.

The essence of the genetic forest typologies

The concept of forest type in genetic typologies

One of the key elements in the genetic typology is the concept of the forest-forming process. A forest as a natural phenomenon is in a state of continuous development, which occurs also by the accumulation of small quantitative changes in its elements and environmental conditions during its lifetime. These small changes often escape the observer's attention and are usually seen only when they have developed into a qualitative difference that is perceived as a revolutionary change. The forestry process and succession of tree species are interrelated sides of a wider evolutionary process of the geographical landscape. By its nature, it is spiral-cyclic and is divided into stages, which are qualitatively different from each other (Kolesnikov 1956).

According to genetic typologies, the forest type is defined within the type of forest growth conditions, which is determined by a set of the following characteristics: genesis and shape of relief elements, light conditions, physicochemical properties of parent soil-forming rocks, soils, water regime, and water and mineral nutrition of plants. The type of forest within the genetic approach is the stage of the forest-forming process.

Phytocoenosis types are stages of forest development within a forest type, meaning that forest phytocoenoses (forest community) can change each other within the same of forest site conditions. However, many characteristics of phytocoenosis, for example species composition and structure, can differ significantly from each other; otherwise, all of them would belong to the same forest type (Kolesnikov et al. 1974, Smolonogov 1998). The forest type in the genetic classification consists of a series of phytocoenosis types or, in other words, the type of phytocoenosis is a form of forest type existence, and the latter is represented by a genetic series of types of phytocoenosis replacing each other within time (Kolesnikov et al. 1974). The type of forest is characterized by a certain stand development, formed by certain forest-forming tree species.

It should be noted that in natural classifications the type of forest phytocoenosis, the type of forest and the forest biogeocoenosis are considered synonyms, but in the genetic classification the type of forest has a wider concept. The genetic approach to forest type classification does not contradict natural typologies, but rather completes them. Genetic classification relates to natural classifications and can be defined as their continuation (Kolesnikov 1961). Currently, the genetic classification developed by Ivashkevich and Kolesnikov is based on the achievements of Sukachev's natural forest type classification. It is worth noting that Sukachev's forest typology was supplemented by data of the duration, direction and speed of different forest succession types. The successions caused by the morphogenesis of edificatory tree species (Kolesnikov 1974) were separated into a special category and designated ontogenetic succession, which consists of age and recovery (demutational) successions. The latter occurs over the lifetime in no more than two genetically related generations of trees. Within the genetic classification of forest types, it is possible to study the history of individual types of biogeocoenosis and the series of their development, as well as to develop a classification of forest expanse according to the degree of their change due to anthropogenic impacts.

The most important indicators for determining forest type in genetic classifications are the following: forest-forming and associated wood species; landform; stand development of the forest-forming species, estimated according to productivity of prevailing generation at the maturity (site index class) stage; and characteristics of forest renewal (Kolesnikov 1961). These allow to predict the future of the forest type.

Genetic approach to the classification of forest types and other concepts regarding the representation and analysis of vegetation cover

Even though the first publication relating to succession dates to 1685, most active study of successions followed the works of Hult, published in the late XIX century (Clements 1936). In 1916, Clements proposed the concept of casual successions and monoclimax (Clements 1916, Connel and Slayter 1977). The development of the concept of succession was built up by Tensley (1935) and many other researchers and continues to the present time (Ingegnoli 2002, Capelo 2018).

One year before the classical work of Clements (1916), Ivashkevich published the results of his study of forests in Manchuria (Kolesnikov 1956, Smolonogov 1998, Shorohova et al. 2009, Brumelis at al. 2011). He formulated the basic ideas of the genetic approach to the classification of forest types, including the revealing of forest types, considering their succession dynamics and climax state of forest vegetation. He completed the first genetic classification of the Primorye forests in the Far East in the late 1920s (Ivashkevich 1927). All principles of the genetic approach that are applied in modern genetic classifications were implemented in this classification, including strict regional binding for each complex of forest types; identification of primary and secondary forest types in certain site types; consideration of altitudinal zonality, relief forms and soils in determining the types of site conditions; a brief description of the composition of the stand and the understory vegetation; as well as a general description of the productivity of forest stands.

It should be noted that the concepts which Ivashkevich used in his works corresponded to or exceeded existing analogues built up by that time for several aspects. For example, he distinguished the main type of forest, called the primary forest type in modern terminology. The criteria he used to define this type are like the concepts of the climax pattern or site climax that were created much later in the 1950s (Meeker and Merkel, 1984).

The development of the principles of the genetic approach to the classification of forest types and the development of the first genetic classifications in Russia occurred during a difficult period in the social life of the society that included the First World War, the October Revolution, and the subsequent Civil War that swept across all regions of the Russian Empire, including the Far East. During this period, information exchange between Russian and foreign researchers was difficult or even impossible. Despite these difficulties, one of the most advanced classifications of forest types was elaborated in Russia, which conceptually and technologically corresponded to the state-of-the-art in this field.

Kolesnikov improved and developed several ideas laid upon by his teacher in the field of forest and forestry zoning of the territory and the elaboration of genetic forest typology schemes, and he promoted the introduction of genetic typologies into the practice of forest management in different regions of the fSU.

The development of scientific thought in vegetation sciences in other countries also led to the creation of several modern concepts, some aspects of which overlap with a number of provisions of the genetic approach to the classification of forest types. The revealing of forest-forming epochs and the classification of forests according to the degree of anthropogenic impacts elaborated by Kolesnikov (1974) can be correlated with the concepts of the integrity and naturalness of forests that have been actively developed in several western countries since the second half of the 1970s (Anderson 1991, Angermeier and Karr 1994, Angermeier 2000, McRoberts et al. 2012).

Studies by Giacomini, Tuxen, Gehu, Beguin, Hegg and Rivas-Martinez led to the creation of the concept of synassociations (Ingegnoli 2002, Capelo 2018). In phytosociology in the 1970s, based on the concepts of Clements' climax and the concept of the association of vegetation, a transition from the definition of the relationships between plant associations that form the vegetative elements of the landscape to series and chains of types that appear (and change each other) within a certain territory occurs. Obviously, this concept coincides with the principles of the genetic approach to the classification of forest types over several parameters.

Despite the difficulties in assessing the naturalness of forests, international interest in silvicultural practices that mimic natural processes in forest ecosystems has increased in recent years (McRoberts et al. 2012). From this point of view, the achievements of Soviet and Russian forest typologists in the field of formulating genetic classifications that make it possible to use the features of the forest formation process for the purposes of forest management are in line with current worldwide trends in the field of forest sciences.

Forest-forming epochs

To consider the level of anthropogenic impacts on forests in analyzing the formation of forest types, Kolesnikov identified three forest-forming epochs: preagricultural; spontaneous and unplanned use of forest resources by humans; planned use and conscious transformation of forests (Kolesnikov 1961). They differ in the degree and depth of human impact on the forest, as well as by the forms and technical facilities of impact.

In the preagricultural epoch, the greatest impact on the forest was through forest fires. In this case, the turnover of fires, i.e., the period between repeated fires was several decades, and for hard-to-reach areas, for example, in the upper mountain belt, the period was centuries. The epoch of spontaneous and unplanned use of forest resources is characterized by industrial logging, including mechanized logging at the end of this period. The turnover of fires was reduced to decades and several years. The epoch of conscious planned use and transformation of forests is characterized by intensive forest cutting and creation of artificial forests.

During the preagricultural epoch, the age and recovery succession in forest types reached the end and turned into century-old succession coordinated with the zonal-climatic changes of the geographical landscape. In the epoch of spontaneous unplanned use of forest resources, natural and century-old succession were suppressed or complicated by reforestation processes that rarely lead to the formation of forest types that fully correspond to the zonal-climatic features of the geographical landscape. Nevertheless, in this period, the forest-forming process was regulated by the laws of the age-old evolution of the natural landscape, although weakened or interrupted by human influence. In the epoch of planned use and conscious transformation of forests, each of the stages of the forest-forming process was under anthropogenic influence, expressed in the suppression or modification of the natural patterns of forest development.

Currently, forests in different parts of Russia consist of forest types typical for different forest-forming epochs. Therefore, in the genetic classification, it is necessary to take into account the features of the forest-forming process specific to them, meaning that it is necessary to divide the territory into categories that correspond to these epochs. To understand the forest-forming process patterns, it is necessary to carefully consider the nature and forms of human impact on forests (Kolesnikov 1961).

Classification of forests by the degree of economic use

Kolesnikov (1974) also developed a classification of taiga forest expanse in terms of human economic activity impact level (Figure 1). It consists of three large classes.

Virgin forests

These were not affected by any human beings, including through indirect human economic activity. They are typical for the preagricultural epoch of the forest-forming process. Onto-, holo- and phylogenetic successions dominated in these forests. This class of forest disappeared by the end of the XIX to the beginning of the XX century.

Primary forests

These are not directly affected by human economic activity. Such forests are typical for the preagricultural epoch of the forest-forming process, as well as for the epoch of spontaneous and unplanned use of forest resources by humans for remote and sparsely populated areas. Primary forests are characterized by features of the dynamics of virgin forests with an increasing role of postfire successions.

Modern forests consist of two subclasses:

Natural forests

These were affected directly and indirectly by economic activity but have already eliminated the consequences of

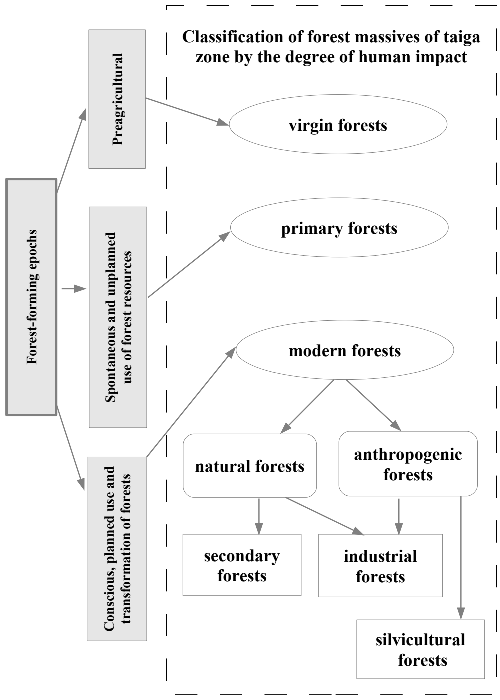

Figure 1. Classification schema of forest tracts of taiga zone by the degree of human impact

these impacts or are at the stage of such elimination. They are developing without any obstacles according to the natural laws of the forest-forming process. The phenomena of onto- and hologenesis (anthropogenic) dominate in these forests. Modern forests can be found in sparsely populated area and in areas with little impact of the forestry industry.

Anthropogenic forests (forests of the future)

These are affected by repeated and various human impacts during economic activity. They are in the sphere of constant human influence, which modifies the natural forest-forming process. These forests are partly created by humans. They are typical for the epoch of planned use and conscious transformation of forests. Each of these subclasses is divided into the following groups (Figure 1), one of which belongs to both:

a) *Secondary forests* (refers to natural forests). These are formed after a single and strong impact, for example, because of felling, forest fire or melioration. The consequences of these impacts in forests are not yet eliminated. These forests develop spontaneously. These forests are in the initial stages of reforestation (demutational successions). Secondary forests are typical for the era of planned use and conscious transformation of forests. They are typical for developed industrial areas.
b) *Industrial forests* refer to both natural and anthropogenic forests. The reason for their occurrence is the same as for secondary forests, but they are under the permanent control of foresters, who regulate the stages of the forest-forming process by using partial intermediate fellings, melioration, use of pesticides, etc. In these forests, demutational and digressive successions

prevail, and phylogenesis is distorted. These forests can be found in economically developed regions.

c) *Cultural forests* (refer to anthropogenic forests). These were created in accordance with the requirements of forestry, but often without accordance with features of the forest-forming process, or even against them. They are under permanent control of foresters. The initial stages of ontogenesis (age successions and generation changes) are typical for such forest. Digressive successions and syngenesis caused by technogenic influences can be often found in these forests.

On the basis of an analysis of the materials written by Tyulina, Filroze, and a number of other researchers, Kolesnikov (1974) estimated standing crop changes of cowberry pine forest in the subzone close to the forest-steppe zone in the Southern Urals: starting from 600 m^3/ha in primary forests (XVIII century), up to 500–350 m^3/ha in secondary forests (1800s–1920s), up to 200–100 m^3/ha in the industrial forests (1920s–1970s) and up to 500 m^3/ha in anthropogenic forests, created by the method of forest cultures with the use of fertilizers and the application of melioration (forests of the future).

These data indicate that the system of forestry practices, considering the specific features of the forest-forming process, makes it possible to realize the potential productivity by the timely use of certain operations at different developmental stages of dominant generation. Rational forest management systems should be differentiated by forest types or groups of forest type.

Taxonomy of genetic forest typology

Principles for the classification of taxonomic units, starting with an elementary biogeocoenosis, as well as variants of the hierarchy of taxa, are given in publications by Kolesnikov (1956, 1961, 1974), Sochava (1961), Smagin (1973), Smolonogov (1998) and Manko (2013). A map of the distribution of the genetic approach to the classification of forest types in the fSU by the end of the 1970s is shown in Figure 2a. A map showing the regions of the Russian Federation currently using forest typologies based on the genetic approach is shown in Figure 2b. For mapping we used data obtained on official requests from forest inventory enterprises and information from official regional forest plans of the Russian Federation. Based

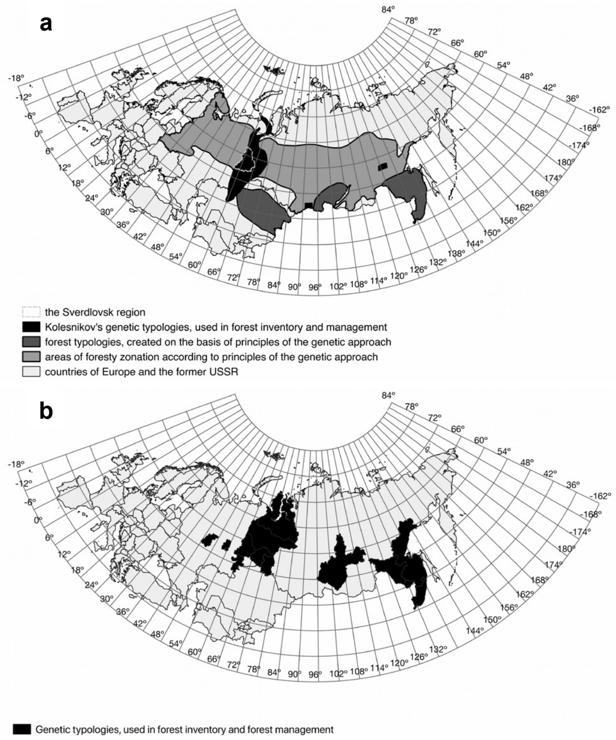

Figure 2. Map of the distribution of genetic classifications within the fSU at the end of the 1970s (a) and nowadays (b)

on the results of long-term research, Smolonogov (1998) compiled a generalized relation schema of classification units and series of genetic forest typology (Table 1).

The differentiating categories for the territorial classification are as follows: ranks of regions with different forest growth conditions, altitudinal belts in the mountains, orographic structures and their elements, soil-forming rocks and soils, moistening regime, light conditions, phytocoenotic factors and features of the recovery-age dynamics of forest communities. The results of forest zoning for Sverdlovsk Region are shown in Figure 2, whereas Tables 2 and 3 give classification schemes of the types of forest conditions and forest types built up by Kolesnikov, Zubareva and Smolonogov (1974). They are still used by forest inventory enterprises when carrying out forest inventories in Sverdlovsk Region.

Table 1. Generalized schema of interrelationship of classification units and ranges of site conditions, forest phytocoenosis (forest community), biocoenosis (forest ecosystem) and genetic forest typology

Ranks	Series			
	Site conditions	Forest phytocoenosis (Forest community)	Forest biogeocoenosis (Forest Ecosystem)	Genetic forest typology
Altitudinal belts	Altitude complex of forest growth conditions	Altitude complex of forest phytocoenosis	Altitude complex of forest biogeocoenosis	Altitude forest typology complex
Orographic	Set of forest growth conditions	Orographic complex of forest phytocoenosis	Orographic complex of forest biogeocoenosis	Orographic complex of forest types
Basic	Type of forest site condition	Set of forest phytocoenosis	Set of forest biogeocoenosis	Forest type
Elementary	Ecotope	Elementary forest phytocoenosis	Elementary forest biogeocoenosis	none

Table 2. Fragment of the table – schema of forest site classification and forest types of the southern taiga forest growth conditions district (C-VIv) of the Zauralsky (Trans-Ural) hilly piedmont province, the West Siberian Forest Region, developed by Kolesnikov et al. (1974)

Site conditions				Forest types				
Altitudinal class, elevation above sea level, m	Group of types according to moisture regime	Types according to features of relief, soils and other characteristics	Index	Primary or nominally primary, site index class abbreviation	Felling		Secondary	
					Natural	Burn	Short-term	Long-term and steady
3. Low-mountain and piedmont, 200–500 meters	2. Fresh, periodically dry	1. Mountain top and upper parts of slopes with shallow mountain-forest low-podzolized soils	321	*Pinetum vacciniosum*, II-III, *Pn.vac.*	*Calamagrostidosum*	*Calamagrostidosum*	*Pinetum, Pinetum-Betuletum Vaccinio-calamagrostidoso-chamaecytisum*	*Pinetum-Betuletum vaccinio-calamagrostidoso-chamaecytisum*
	4. Fresh, periodically moist	3. Drained lower parts of the near-valley part of the slope, low ridges between the swamps with sod-podzolic heavy soils with features of gleying	343	*Piceetum herbosa-hylocomiosum*, II-III-IV, *Pc.her.hyl.*	*Herbosa-calamagrostidosum*	*Calamagrostidosum*	*Betuletum-Tremuletum herbosum* with dark conifer layer	*Betuletum-Tremuletum, Tremuletum herbosa-calamagrostidosum*

Table 3. Fragment of the table – characteristics of the primary (or nominally primary) *Pinetum vacciniosum* and *Piceetum herbosa-hyloicomiosum* forest types, at the mature or overmature stages for the southern taiga forest growth conditions district (C-VIv) of the Zauralsky (Trans-Ural) hilly piedmont province, the West Siberian Forest Region, developed by Kolesnikov et al. (1974)

Index of site conditions	Forest type	Tree stands (characteristics of stand composition, site index class, normality, stock of a stand per 1 hectare)	Regeneration (species composition, density level)	Undergrowth species composition, density of features of spatial distribution)	Ground cover (covering, dominant grass and moss sublayers)
321 / Pn.vac.	*Pinetum vacciniosum*	*Pinus sylvestris* L. with *Betula pendula* Roth., or sometimes *Larix sukaczewi*; site index class: II (II–III); 0.6–0.8; growing stock: 270–350 m^3; often on fire	Abundant – *Pinus sylvestris* L. with single trees of *Larix sukachevii* and *Betula pendula* Roth.	*Sórbus aucupária* L., plants of the genus: *Cytisus, Juníperus, Rosa*	Dominating: *Vaccinium vitis-idaea* L; abundant: *Rubus saxatilis* L., *Fragaria vesca* L. plants of the genus: *Calamagrostis*, fine herbage; rare spots of green moss, cover 0.5–0.8
343 / Pc.her. hyl.	*Piceetum herbosa-hylocomiosum*	*Picea abies* (L.) H.Karst., *Abies sibirica* Ledeb., with single trees of *Pinus sibirica* Du Tour, *Betula pendula* Roth., *Pinus sylvestris* L., *Larix sukaczevi*; site index class: II–III; growing stock: 300 m^3	Good – main forest-forming species, curtained	Single plants of *Lonicera caerulea* L., *Ribes rubrum* L., plants of the genus: *Spiraea, Tília, Rosa*	Background of unevenly planted green mosses of the genus *Calamagrostis*, *Gymnocarpium dryopteris* Adans, *Rubus saxatilis* L., plants of the genus *Oxalis* L., forest forbs

The genetic classifications contain several classification series that represent the spatial amplitude of taxonomic units, as well as their ecological and structural differentiation. When elaborating classification schemes for forest types, unified classification principles are employed for any geographical areas, and, if possible, forest ecosystems of all levels of integration (from elementary to higher level) and their possible changes in time are considered.

Smolonogov defined the following classification (ordinational) series: forest site conditions, forest phytocoenotic, forest biogeocoenotic, and forest typology (Table 1). He also described the landscape series, although it is not used in the practice of forest inventory and forestry. Ranks consist of the following units: elementary, basic, orographic, and altitudinal belts. Ecotope is an elementary classification unit of several forest growth conditions. It is a set of environmental elements and ecological factors that determine the specificity of the site conditions. The characteristics of the ecotope are stable over time. They can serve as a basis for identifying more complex classification units in other series. For example, the ecotope corresponds to the elementary units of the forest phytocoenotic and forest biogeocoenotic series, i.e., forest phytocoenosis and forest biogeocoenosis, respectively (Table 1). The basis for determining the elemental forest phytocoenosis boundary is the forest tree species that form closed forest stands. The concept of elementary forest biogeocoenosis is related to the concept of type forest biogeocoenosis or forest type in the interpretation of Sukachev (1957).

The components of forest biogeocoenosis relate to a forest-forming process, which can be revealed in time in the form of recovery-age morphostructural and functional changes of biogeocoenosis. The components of elementary forest biogeocoenosis can be described or measured, and some interrelations between them can be found. For all larger integral units of the classification, only average characteristics are given, and possible variants of their variation in time are established.

The forest site type (FST) is the main classification unit of forest growth conditions. In climatically homogeneous areas the FST is a combination of ecotopes similar in the following characteristics: the genesis and shape of relief elements or geomorphological structures (different parts of watersheds, slopes, floodplain terraces), light conditions, physicochemical properties of soil-forming rocks and soils, water regime and water-mineral nutrition of plants.

The forest type in the genetic typology is represented by a genetic series of forest phytocoenosis types within the conditions of forest type site, or a series of forest types, replacing each other over time (Table 1). Primary and secondary forests represent the primary forest type in the genetic forest typology (Kolesnikov et al. 1974, Smolonogov 1998).

The orographic complex of forest growth conditions within mountainous and flat territories unites some of these conditions in various elements of geomorphological structures that define the specificity of ecological impacts on forest vegetation: temperature and water regimes, light conditions, and soils. The orographic complexes of forest phytocoenoses and biogeocoenoses correspond to the orographic complex of forest growth conditions (Table 1).

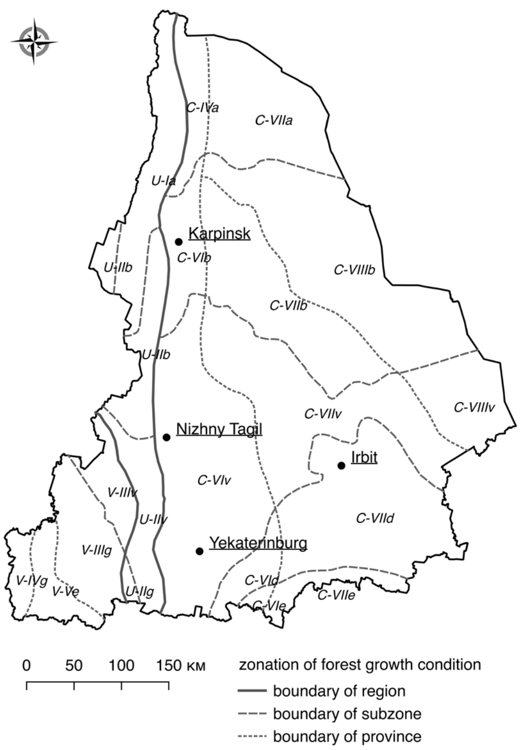

Figure 3. Map of the forest-forming zoning of Sverdlovsk Region. Roman numerals denote forest districts – the smallest units of the territory. Each district has common forest growth conditions. A unique classification table with genetic forest types was developed for each district

The altitude complex of forest growth conditions is the largest taxonomic rank for mountainous areas. For mountain systems that are not divided by altitude belts, as well as for flat areas, regional complexes of forest growth conditions located within regions with specific forest site conditions (a forest subzone, district or area) can be considered in the same way.

A map of forest site zoning of Sverdlovsk region is shown in Figure 3. The forest district is the smallest area with relatively homogeneous forest growth conditions formed because of the intersection of large territorial units: forest region, subzone and province. For each forest district, classification schemes with forest site types (Table 2) and forest types have been developed (Table 3). The forest zoning according to forest growth conditions was carried out by specialists under the guidance of Kolesnikov in the area including the European part of Russia and a significant part of western and eastern Siberia, as well as part of the Far East (Figure 2).

The altitude complex consists of areas covered and uncovered by forest within a region with specific forest growth conditions. These areas must be like each other in general with respect to the macro- and meso-climate, features of the relief, soil-forming rocks, and a number of other characteristics. The altitude complexes of forest phytocoenoses, forest biogeocoenoses and forest types correspond to altitude complexes of forest growth conditions (Table 1).

Each taxonomic unit of forest site conditions is denoted by a three-digit numeric index and is written sequentially from left to right, beginning with an altitude complex of forest growth conditions and ending with a numerical value of the type of forest site condition. Thus, a three-digit integer corresponds to each type of forest condition. The rules with index addition proposed by Sukachev are used for the designation of forest type (Table 2). A sample coding of indices of forest site types on the altitudinal profile of the Urals with three forest districts is shown in Figure 4.

Considering the influence of natural and anthropogenic factors

Genetic typologies and anthropogenic impacts on forests

In the genetic forest typology, great attention was given to anthropogenic impacts, especially felling, on the reforestation and development of forests. With the approval and support of Kolesnikov (Manko 2013), Sannikov began to develop a model for postcatastrophic divergence-convergence of ecological and dynamic series for the renewal and development of biogeocoenosis within forest types (Sannikov 1970, Sannikov 2009a). The success of postcatastrophic reforestation of the coenopopulation of the main forest-forming species determines the combinations of the following leading factors: the type and intensity of the ecological catastrophe, conservation of the stand and

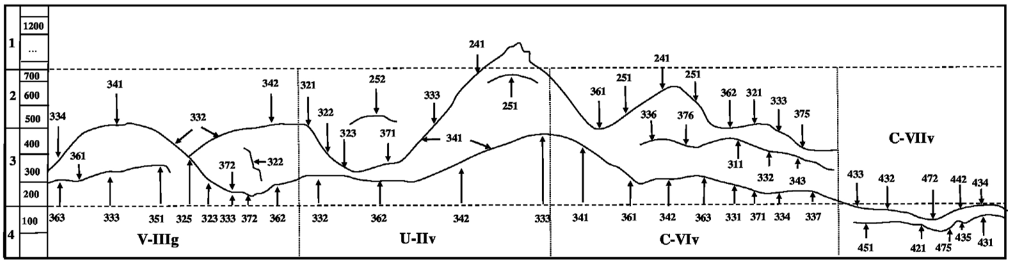

Figure 4. Sample schema for coding of forest site condition on the altitudinal profile of the Urals by example of the three forest districts

the growth of the main tree species, the level of seeding of the main species, and the prevailing substrate for natural regeneration (Sannikov 1970).

Sannikov created a differentiation scheme of site conditions and ecological series for the renewal and development of phytocoenosis after the destruction of the primary type of phytocoenosis in the *Pinetum Vaccinio-myrtillosum* and *Pinetum Myrtillo-hylocomiosum* forest types (Sannikov 1970, Sannikov et al. 2012). He also developed a series of climatically replacing pine forest types for the above-floodplain terraces of the Trans-Urals (Sannikov 1974).

According to Sannikov's interpretation, the type of forest differs from the typical definition for the early stages of the development of the genetic typology of representations regarding type of forest as one monolinear recovery-age series of successions of biogeocoenoses within the type of forest-growing conditions. According to Sannikov, forest type can be represented as a set of alternative horologically isolated series (bundles) of their divergence and convergence, with each of them periodically implemented under the influence catastrophes (Sannikov et al. 2014).

After clear felling, there are numerous possibilities of recovery-age dynamics for forests. However, it is very difficult to create ordered schemes for forest management decisions. That is why it is necessary to systemize phytocoenosis according to homogeneity principles of growth, development and formation of stands. Homogeneity in development of such stand series is provided, first, by the uniformity of the reforestation process (Tsvetkov 2009).

The homogeneity of phytocoenosis development, which can be represented in the dynamic series of phytocoenosis types according to the similarity of the starting conditions (the presence and state of the undergrowth vegetation, the nature of the soil substrate and ground cover in the initial type of phytocoenosis and the degree of substrate disturbance by logging operations, and provisioning of seed plants), defined not only by forest growth conditions but also by the uniformity of these conditions within the forest parcel. The properties of forest phytocoenosis are formed according to the same type of genesis in different but ecologically similar initial forest types and can be closer to each other than to forest phytocoenoses formed in one forest type but according to different types of phytocenogenesis (Tsvetkov 2009). A similar conclusion was reached by Sannikov after analyzing forest regeneration on felling areas. He found that differences in environmental factors, abundance and growth of coniferous species on the felling areas with undisturbed coarse humus litter and areas with a burned or mineralized soil surface within the same forest type are significantly larger than between abutting types of forest that have the same soil characteristics (Sannikov et al. 2014).

Pyrogenic dynamics of forests and genetic typologies

Numerous studies regarding recovery and age dynamics of forests in different regions of the Russian Federation have been carried out as part of the genetic approach to the classification of forest types. Sedikh (2009), using the example of the age dynamics of Siberian stone pine *(Pinus sibirica* Du Tour*)* in dark coniferous forests in western Siberia, analyzed the changes in forest conditions, which consisted of increasing the thickness of forest litter, water holding capacity, and soil moisture, and in lowering its temperature. Within several generations of the forest, there is a progressive swamping of habitats and low-production *Pineta sibirici sphagnosum* type forests are being formed in place of *Pineta sibirici hylocomiosum* forest types.

However, the widespread distribution of hydromorphic stone pine forests is hampered by forest fires, which, by destroying the stand and mineralizing the decocted litter, create favourable conditions for forest vegetation on the hills. Its further development takes place according to the scheme of postfire recovery and age dynamics of Siberian pine stone forest. In the dry forests, fires interrupt the swamp-forming process, stimulating the forest-forming process. Thus, they are one of the powerful factors that stabilize forest cover (Sedikh, 2009).

The importance of the role of forest fires as one of the key factors affecting the recovery and age dynamics of forests is evidenced by the results of research in other regions of the Russian Federation. In the pre-forest steppe subzone of western Siberia and *Pineta hylomicosum* group of forest types, cyclically repeated fires are the key exogenous factor affecting pyrogenic spruce change to pine in regeneration and stand composition (Sannikov 2009b). During long-term successions in the zone of transition from forest-steppe to dark coniferous taiga, the pine is the most stable forest-forming species, capable of reforestation after disturbances caused by forest fires with different intensities. Frequent ground fires strengthen the position of pines in comparison with dark coniferous and deciduous species, as well as larch (Konovalova et al. 2009).

It is worth noting that in the classification schemes of forest types of Sverdlovsk region, the pyrogenic factor is strongly considered (Kolesnikov et al. 1974). Table 2 shows the main characteristics for felling.

Climatogenic dynamics of forests and genetic typologies

The necessity of considering the climatogenic dynamics of vegetation in forest typologies has been realized by scientists and forest typologists (Karaziya 2016, Baginsky 2016, Maslov 2016). There are currently few reliable quantitative data confirming the effect of climate change on the typological characteristics of forest biogeocoenosis in the low latitude plain areas of the Russian Federation and the countries of the fSU.

Comparative analysis of 25–30-year data of instrumental observations in the central part of the Russian plain indicates that variation in the typological characteristics of forest phytocoenosis stays within one forest type in the interpretation of Sukachev or type of forest phytocoenosis in the interpretation of Ivashkevich–Kolesnikov (Maslov 2016). The forecast for the development of pine stands of the Belarusian Polesie in connection with climate change, made based on the dynamics of stand volume in several types of forest, indicates that by 2030 there will be no significant changes regarding volume of forest stands in the observed forest types (Baginsky 2016).

Unlike flat areas located in the low latitudes of the Russian Federation, studies of the climatogenic dynamics of forest cover in high mountains and high latitudes have been conducted for longer periods. This relates to the fact that forest cover growing in extreme climatic conditions of highlands and northern latitudes is very sensitive to climate change, and therefore it can be used as an indicator of climatogenic changes occurring in forest communities and tundra.

In the Ural region, systematic studies of the spatiotemporal dynamics of woody vegetation in the tree line ecotone in the Polar, Northern and Southern Urals have been conducted from the mid-20th century (Moiseev and Shiyatov 2003, Davy et al. 2008, Kammer et al. 2009, Moiseev et al. 2010, Mazepa et al. 2011, Grigor'ev et al. 2013, Hagedorn et al. 2014, Shiyatov and Mazepa 2015). Regional warming and climate humidification in the Urals in the second half of the 20th century (Shalaumova et al. 2010) led to the vertical shift of woody vegetation in the high mountains of this region (Shiyatov et al. 2005, Kapralov et al. 2006, Shiyatov et al. 2007).

The abovementioned areas are characterized by very low anthropogenic impacts and are good model areas for the study of succession stages in plant communities, primarily changes of tundra plant communities to forest communities (*via* forest-tundra communities). Studies of the spatiotemporal dynamics of woody vegetation in the tree line ecotone make it possible to distinguish the formation stages of forest type – a series of phytocoenoses types within the types of site conditions.

One important research area for site climate characteristics used in determining forest type is the study of phenomena associated with the thawing of permafrost (Agafonov et al. 2004, Camil 2005, Olsson 2009, Howard 2014). It should be mentioned that regional climate change affects the presence and duration of wildfires (Ponomarev et al. 2016). Fires have a significant impact on forests, soils, permafrost dynamics, regional climatic conditions and carbon balance (Olsson 2009, Brown et al. 2015, Abis and Brovkin 2017). Therefore, the impact of climate change on the spatial and temporal dynamics of forests can be considered in genetic typologies indirectly, through the analysis of their post-pyrogenic forest recovery dynamics.

Technological aspects of genetic typologies

Cartography and geoinformation technologies in genetic typologies

The development of genetic classifications according to regional and typological principle is impossible without the development of geobotanical and landscape cartography (Sochava 1961). Maps of forest types are essential for forest management (Farber 2014). Mapping of forest types is closely related to classification issues. The practical and scientific value of maps is determined by the principles in the classification. The legend of the map is based on the classification results (Filroze 1970, Ryzhkova et al. 2009).

Typically, in forest type maps, the colours used are very close to the colour of the dominant tree species. The background colour indicates the primary forest type, and the colour of the hatching is used for the secondary forest type. There are stripes of different widths to display certain stages of succession, and bands of different tones are used for denoting reversible and irreversible successions (Filroze 1970). One of the most significant drawbacks of this approach is the difficulty in reading the map due to the density of details. The imperfection of such a notation system is presented by numbers of symbols that are significantly fewer in numbers than the number of forest types. Forest types differ from each other significantly because of site conditions. This leads to the fact that on a map vegetation plays more role than physiographic conditions, which also determine specificity of forest types (Filroze 1970).

Development of geoinformation technologies has opened to a considerable extent the unrealized potential of the automated classification of forest site conditions, which is used by the creators of the genetic approach in forest type classification. Modelling in geoinformation systems of the parameters of the topographic position of forest areas for assessing the characteristics of habitats has been widely used in environmental studies for some time (Davis and Goetz 1990, Mackey et al. 1994, Guisan and Zimmermann 2000, Rich and Fu 2000, Ray and Broome 2003, Hong et al. 2004, Klinge et al. 2015, Parresol et al. 2017). Since in the genetic forest typology the form of the relief within the forest type is one of the most significant indicators (Kolesnikov 1961), developing methods for automated classification of site conditions and forest types, as well as mapping forest cover with a digital elevation model (DEM) and remote sensing data, have great importance in forestry for the Russian Federation (Sedikh 2005, Ryzhkova, et al. 2009, Danilova et al. 2010, Fomin and Zalesov 2013, Farber 2014).

One of the most successful modern developments in this area is the method of automated mapping of forest recovery dynamics based on DEMs, multispectral satellite images and results of ground surveys (Ryzhkova et al. 2009, Ryzhkova et al. 2011). The method allows a researcher to build the DEM-composite layer with values of the absolute height, slope and curvature of the surface. Using automated classification algorithms and spatial analysis via multispectral satellite images and a DEM-composite layer, forest areas with relatively homogeneous site conditions are revealed and a map of forest vegetation recovery dynamics is generated. This method has been successfully tested in the Middle Cis-Angarian area of more than 1,000 km^2 (eastern Siberia, the Russian Federation). The authors used a SRTM90 model, Landsat ETM+ satellite images, and archived and public data, as well as the results of field studies (Ryzhkova et al. 2009, Danilova et. al. 2010).

The increased accessibility of aerial lidar scanning data and small-sized aircraft, as well as high spatial resolution satellite data, provide researchers with great opportunities to develop methods for automated data collection regarding composition of stands and their forestry-taxation characteristics that can be used as technological elements for "virtual" forest inventories (Wulder and Seemann 2003, Hinker at al. 2008, Othmani at al. 2013, White at al. 2013, Montesano at al. 2014).

Practical use of genetic typologies

Kolesnikov (1961) believed that during the determination of forest type, along with the growth conditions of the site, special attention should be paid to the analysis of the stand structure, primarily the age structure and its productivity. Several studies have been devoted to features of the structure of stands in different types of forest and the variation of morphometric parameters, depending on the forest-growing conditions (Smolonogov 1970, Smolonogov and Trusov 1970, Soloviev 2009). In particular, Smolonogov (1970) developed quantitative criteria for carrying out a comparative analysis of the productivity of forest-growing conditions, assessing the nature of tree differentiation depending on the composition of the stands, including allowing them to be used to establish the connection between the processes of tree differentiation with age and the density of stands.

The genetic approach was widely recognized, along with the geographic and genetic classifications elaborated for the forests of the Russian Far East (Kolesnikov 1956, 1961, 1967, Manko 2013, Zhabyko 2013), the Urals (Kolesnikov et al. 1974, Martynenko and Shirokih 2013, Martynenko et al. 2016), Siberia (Smolonogov 1995a, 1995b, Sedikh 2005, Ryzhkova et al. 2009), and several central regions of the Russian Federation. Despite the decline of the development and improvement of forest typologies since the beginning of the 1990s, which was due to several social and economic reasons, nevertheless forest typological studies, including the genetic approach to the classification of forest types, are actively pursued.

The prospects for future development of genetic typologies

In our opinion, the development of ideas within the genetic approach to forest classification and the improvement of the already developed genetic classifications and development of new ones will proceed in the following main directions:

The improvement of technologies for automated forest zoning according to site condition

This will be achieved due to the development of geoinformation technologies in obtaining high resolution spatial data, increasing their accessibility for researchers, and to the emergence of new mathematical models and methods for processing and analyzing spatial data. Currently existing functions of morphometric and hydrological analysis of DEM for quantitative assessment of the topographic position of forest sites and the levels of impact of leading ecological factors allow researchers to quantify several important forest site conditions.

Actual tasks within this line of research are as follows:

- Development of spatial models for the quantitative assessment of environmental factors, which determine main conditions for growth and forest development;
- Development of rules that allow researchers to unite forest sites with different but similar sets of parameters that characterize forest-growing conditions, i.e., to carry out automated allocation of boundaries of terrain units with a certain type of forest site conditions.
- Development of models that allow obtaining integral level assessments regarding favourable conditions for forest growth, thus quantifying potential forest-growing influence of a particular site for forest cover.
- Development of new methods for estimating forest taxation characteristics of tree stands via high spatial resolution data using aerial drones.

The re-establishment and improvement of technologies for repeated forest inventory systems to obtain data on the spatiotemporal dynamics of forest cover

The stationary method of studying the productivity of forest communities in single-time measurements and descriptions, which is widely used in forest typological studies, does not allow determination of large-scale phenomena, for example, the age-old dynamics of geographical landscapes, and the age and recovery dynamics of forest biogeocoenoses (Kolesnikov and Filroze 1967). Repeated stationary methods eliminate some of these deficiencies, but they require long-term observations. It should be noted that it is often impossible to carry out repeated observations at remote locations or inaccessible territories. Moreover, such observations are expensive. Therefore, according to Kolesnikov, stationary research should be supplemented with other methods including as example statistical methods that are used in repeated forest inventories. These methods should be used for building or improving some genetic forest type classifications.

It must be considered that genetic forest typology schemes were sufficient using the existing technology of repeated forest inventory in the fSU until present. One idea includes carrying out forest inventory fieldwork every 10–20 years (depending on the type and intensity of forest management) by specialized organisations such as forest inventory enterprises on the customer area. After performing such fieldwork, customers obtain forest management plans containing cartographic materials and descriptions of forest sites with taxation parameters of tree stands and a set of instruction for forest management that must be carried out before the next forest inventory. Such materials are the main data source for forest recovery and age dynamics.

Full recognition of the potential of genetic typologies for improving forest management is impossible without the re-establishment and improvement of technologies for repeated forest inventories with new levels of quantitative data regarding forest phytocoenosis. Repeated working plan revisions make it possible to obtain the necessary data regarding changes in forest successions over time and to obtain data regarding site conditions and types of forest phytocoenosis at different times. This means that as the duration of such repeated observations increases, the amount of information about the stages of recovery and age dynamics of forest phytocoenosis in genetic series will also increase. This allows a researcher to improve existing schemes and create new forest typological genetic classification schemes, as well as to develop a rational forest management system that will make full use of the features of the forest-forming process for the formation of highly productive forests.

Improvement of existing forest typological schemes in zones with a high level of anthropogenic impact and development of new schemes

Another important development for genetic typologies is building new typological schemes in zones with high levels of anthropogenic impacts of different natures and levels aside from forestry activities. One of the requirements underlying the genetic approach to forest type classification is the need to combine forest areas by origin and similarity related to developmental processes of forest stands, which ensures the same tree stand development and productivity of phytocoenosis. A decrease in productivity because of, for example, air pollution, affects all components of forest biogeocoenosis. It also eliminates species as indicators of habitats, changing dynamics of forest stand growth. Therefore, it is important to reflect negative impacts of human activities within such zones in forest typological schemes.

Development of new and improvement of the existing forest-typological schemes, taking into consideration changes in forest biogeocoenoses under the influence of climate change

Flora of high-altitude and high-latitude regions, which usually grow in extreme soil-ground and climatic conditions, is a sensitive indicator of climate change (Shiyatov 1993, Kullman 2002, 2007, Shiyatov 2005, 2007, Hellmann et al. 2016). This observation means that these areas hold great promise for the study of climatogenic dynamics of indicators used in determining forest type. Below are given priority areas for studying phenomena caused by climate change:

- changes from tundra plant communities to forest-tundra and forest communities, namely, studying these forest formational processes in non-forested or poorly forested areas;
- phenomena connected with the permafrost thawing, such as changes in soil and hydrological conditions and their influence on the growth and development of forest cover;
- research on the spatial and temporal dynamics of forest fires that have a significant impact on forests, soils, permafrost dynamics, regional climatic conditions and carbon balance.

Genetic studies of populations that make up biogeocoenoses

Issues of origin (genesis) and development of forests are key elements in genetic approach to classification of forest types. Therefore, studies in the genesis of biogeocoenoses grounded in genetic analysis of populations will become the main topic of current and prospective fundamental research within the framework of this approach.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (project No. 18-34-00803 mol_a) and a grant from the Russian Ministry for Education and Science FEUG-2020-0013.

References

Abis, B., and Brovkin, V. 2017. Environmental conditions for alternative tree-cover states in high latitudes. *Biogeosciences* 14: 511–527. https://doi.org/10.5194/bg-14-511-2017.

Agafonov, L., Strunk, H. and Nuber, T. 2004. Thermokarst dynamics in Western Siberia: Insights from dendrochronological research. *Palaeogeography, Palaeoclimatology, Palaeoecology* 209: 183–186. https://doi.org/10.1016/j.palaeo.2004.02.024.

Anderson, J.E. 1991. A conceptual framework for evaluating and quantifying naturalness. *Conservation Biology* 5: 347–352.

Angermeier, P.L. 2000. The Natural Imperative for Biological Conservation. *Conservation Biology* 14: 373–381. https://doi.org/10.2307/2641603.

Angermeier, P.L. and Karr, J.R. 1994. Biological integrity versus biological diversity as policy directives: protecting biotic resources. *Bioscience* 44(10): 690–697. https://doi.org/10.2307/1312512.

Baginsky, V.F. 2016. Dynamics of productivity of pine stands of Belarusian woodlands by types of forest in connection with climate change. In: Pugachevskiy, A.B., Grummom, D.G., Zelenkevich, N.A. et al. (Eds.) Forest typology: modern methods for distinguishing forest types, classification and zoning of forest vegetation. Kolorgrad, Minsk, p. 73–83.

Brown, D.R.N, Jorgenson, M.T. Douglas, T.A. et al. 2015. Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. *Journal of Geophysics Research Biogeosciences* 120: 1619–1637. https://doi.org/10.1002/2015JG003033.

Brumelis, G., Jonsson, B., Kouki, J., Kuuluvainen, T. and Shorohova, E. 2011. Forest naturalness in northern Europe: perspectives on processes, structures and species diversity. *Silva Fennica* 45: 807–821, article id 446. https://doi.org/10.14214/sf.446.

Camill, P. 2005. Permafrost Thaw Accelerates in Boreal Peatlands During Late-20th Century Climate Warming. *Climatic Change* 68: 135–152. https://doi.org/10.1007/s10584-005-4785-y.

Capelo, J. 2018 Evidence of a unique association between single forest vegetation-types and serial sequences: Praise for the concept of 'vegetation series.' In: Greller, A.M., Fujiwara, K. and Pedrotti, F. (Eds.) Geographical Changes in Vegetation and Plant Functional Types. Springer International Publishing, New York, p. 3–18.

Clements, F.E. 1916. Plant succession. An analysis of the development of vegetation. Carnegie Institution of Washington, Washington, 512 pp.

Clements, F.E. 1936. Nature and Structure of the Climax. *Journal of Ecology* 24: 252–284. https://doi.org/10.2307/2256278.

Connell, J.H. and Slatyer, R.O. 1977. Mechanisms of Succession in Natural Communities and Their Role in Community Stability and Organization. *The American Naturalist* 111: 1119–1144.

Danilova, I.V., Ryzhkova, V. and Korets, M.A. 2010. The algorithm of automated mapping of the current state and dynamics of forests based on GIS. *Bulletin of NSU. Series: Information technology* 8: 15–24.

Davis, F.W. and Goetz, S. 1990. Modelling vegetation pattern using digital terrain data. *Landscape Ecology* 4: 69–80. https://doi.org/10.1007/BF02573952.

Devi, N., Hagedorn, F., Moiseev, P., Bugmann, H., Shiyatov, S., Mazepa, V. and Rigling, A. 2008. Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. *Global Change Biology* 14: 1581–1591. https://doi.org/10.1111/j.1365-2486.2008.01583.x.

Farber, S.K. 2014. Structuring forest communities. *Siberian Journal of Forest Science* 1: 35–49.

Filroze, E.M. 1970. Problems and methods of typological mapping of forests. In: Kolesnikov, B.P. (Ed.) Problems and methods of typological mapping of forests. The Ural Branch of the Academy of Sciences of the USSR, Sverdlovsk, p. 153–174 (in Russian).

Fomin, V.V. and Zalesov, S.V. 2013. Geographic and genetic approach to the evaluation and prediction of forest resources using GIS-technologies. *Agrarian Bulletin of the Urals* 12: 18–24.

Fomin, V.V., Zalesov, S.V., Popov, A.S. and Mikhailovich, A.P. 2017. Historical avenues of research in Russian forest typology: ecological, phytocoenotic, genetic, and dynamic classifications. *Canadian Journal of Forest Research* 47: 849–860. https://doi.org/10.1139/cjfr-2017-0011.

Grigor'ev, A.A., Moiseev, P.A. and Nagimov, Z.Y. 2013. Dynamics of the timberline in high mountain areas of the nether-polar Urals under the influence of current climate change. *Russian Journal of Ecology* 44: 312–323. https://doi.org/10.1134/S1067413613040061.

Guisan, A. and Zimmermann, N.E. 2000. Predictive habitat distribution models in ecology. *Ecological Modelling* 135: 147–186. https://doi.org/10.1016/S0304-3800(00)00354-9.

Hagedorn, F., Shiyatov, S.G., Mazepa, V.S. et al. 2014. Treeline advances along the Urals mountain range – driven by improved winter conditions? *Global Change Biology* 20: 3530–3543. https://doi.org/10.1111/gcb.12613.

Hellmann, L., Agafonov, L., Ljungqvist, F.C. et al. 2016. Diverse growth trends and climate responses across Eurasia's boreal forest. *Environmental Research Letters* 11: 1–12. https://doi.org/10.1088/1748-9326/11/7/074021.

Hilker, T.H., Wulder, M.A. and Coops, N.C. 2008. Update of forest inventory data with lidar and high spatial resolution satellite imagery. *Canadian Journal of Remote Sensing* 34: 5–12.

Hong, S.-K., Kim, S., Cho, K.-H. et al. 2004. Ecotope mapping for landscape ecological assessment of habitat and ecosystem. *Ecol Res* 19: 131–139. https://doi.org/10.1111/j.1440-1703.2003.00603.x.

Howard, B.C. 2014. Drunken Trees: Dramatic Signs of Climate Change. *National Geographic Magazine* (4). Available online at: https://news.nationalgeographic.com/news/2014/04/140417-drunken-trees-melting-permafrost-global-warming-science/ (last accessed on 30 October 2020).

Ingegnoli, V. 2002. Landscape Ecology: A Widening Foundation. Springer Verlag, Berlin–Heidelberg, 357 pp.

Ivashkevich, B.A. 1927. Types of Primorye forests and their economic importance. In: Savich, V.M., Chepurkovskiy, E.M. (Eds.) Productive forces of the Far East. Vol 3. Knizhnoye delo, Khabarovsk–Vladivostok, p. 3–20.

Kammer, A., Hagedorn, F., Shevchenko, I., Leifeld, J., Guggenberger, G., Goryacheva, T., Rigling, A. and Moiseev, P. 2009. Treeline shifts in the Ural Mountains affect soil organic matter dynamics. *Global Change Biology* 15: 1570–1583. https://doi.org/10.1111/j.1365-2486.2009.01856.x.

Kapralov, D.S., Shiyatov, S.G., Moiseev, P.A. and Fomin, V.V. 2006. Changes in the composition, structure, and altitudinal distribution of low forests at the upper limit of their growth in the Northern Ural Mountains. *Russian Journal of Ecology* 37: 367–372. https://doi.org/10.1134/S1067413606060014.

Karazia, S.P. 2016. The history of Lithuanian forest typology classification and current state. In: Pugachevskiy, A.B., Grummo, D.G., Zelenkevich, N.A. et al. (Eds.) Forest typology: modern methods for distinguishing forest types, classification and zoning of forest vegetation. Kolorgrad, Minsk, p. 11–13.

Klinge, M., Böhner, J. and Erasmi, S. 2015. Modelling forest lines and forest distribution patterns with remote-sensing data in a mountainous region of semiarid central Asia. *Biogeosciences* 12: 2893–2905. https://doi.org/10.5194/bg-12-2893-2015.

Kolesnikov, B.P. 1956. Siberian pine forests of the Far East. *Botanical Series* 2(4). Publishing House of the Academy of Sciences of the USSR, Moscow–Leningrad, 261 pp. (in Russian).

Kolesnikov, B.P. 1961. Genetic classification of forest types and its tasks in the Urals. In: Materials of the Institute of Biology of the Ural Branch of the Academy of Sciences of the USSR. Vol. 27, p. 47–59 (in Russian).

Kolesnikov, B.P. 1974. Genetic stage in forest typology and its objectives. *Russian Journal of Forest Science* 2: 3–20.

Kolesnikov, B.P. and Filroze, E.M. 1967. Application of the taxational and statistical method and the genetic classification of forest types. *Russian Journal of Forest Science* 4: 16–25.

Kolesnikov, B.P., Zubareva, R.S. and Smolonogov, E.P. 1974. Forest growth conditions and forest types of the Sverdlovsk region. The Ural Scientific Centre of the Academy of Sciences of the USSR, Sverdlovsk, 175 pp. (in Russian).

Konovalova, M.E., Drobushevskaya, O.V. and Nazimova, D.I. 2009. Recovery and age dynamics of pine grass forests on the transition from forest-steppe to dark coniferous taiga. In: Sannikov, S.N., Shavnin, S.A., Petrova, I.V., and Usoltsev, V.A. (Eds.) Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 129–133 (in Russian with English abstract).

Kullman, L. 2002. Rapid recent range-margin rise of tree and shrub species in the Swedish Scandes. *Journal of Ecology* 90: 68–77. https://doi.org/10.1046/j.0022-0477.2001.00630.x.

Kullman, L. 2007. Tree line population monitoring of Pinus sylvestris in the Swedish Scandes, 1973-2005: implications for tree line theory and climate change ecology. *Journal of Ecology* 95: 41–52. https://doi.org/10.1111/j.1365-2745.2006.01190.x.

Mackey, B.G., McKenney, D.W., Widdifield, C.A., Sims, R.A., Lawrence, K.M. and Szcyrek, N. 1994. A new digital elevation model of Ontario. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario. NODA/NFP Technical Report TR-6, 26 pp.

Manko, Y.I. 2013. The emergence and formation of the genetic forest typology. *Russian Journal of Forest Science* 2: 40–55.

Martynenko, V.B., Shirokikh, P.S., Mirkin, B.M. and Naumova, L.G. 2016. Comparison of different approaches relating to forest classification by the example of the South Ural region. In: Pugachevskiy, A.B., Grummo, D.G., Zelenkevich, N.A. et al. (Eds.) Forest typology: modern methods for distinguishing forest types, classification and zoning of forest vegetation. Kolorgrad, Minsk, p. 45–59.

Maslov, A.A. 2016. Characteristics of forest types under climate change conditions. In: Forest typology: modern methods for distinguishing forest types, classification and zoning of forest vegetation. Kolorgrad, Minsk, p. 107–108 (in Russian).

Mazepa, V., Shiyatov, S. and Devi, N. 2011. Climate-Driven Change of the Stand Age Structure in the Polar Ural Mountains. In: Blanco, J. and Kheradmand, H. (Eds.) Climate Change – Geophysical Foundations and Ecological Effects. *InTechOpen*, p. 377–402 https://doi.org/10.5772/25044.

McRoberts, R.E., Winter, S., Chirici, G. and Lapoint, E. 2012. Assessing Forest Naturalness. *Forest Science* 58: 294–309. https://doi.org/10.5849/forsci.10-075.

Meeker, D.O. and Merkel, D.L. 1984. Climax Theories and a Recommendation for Vegetation Classification – A Viewpoint. *Journal of Range Management* 37: 427–430.

Melekhov, I.S. 1961. Vegetation classification and concentrated forest felling. In: Gorchakovskiy, P.L., Kolesnikov, B.P. and Sochava, V.B. (Eds.) Proceedings of the Institute of Biology, Vol. 27. The Ural Branch of the Academy of Sciences of the USSR, Sverdlovsk, p. 139–145 (in Russian).

Moiseev, P.A. and Shiyatov, S.G. 2003. Vegetation Dynamics at the Treeline Ecotone in the Ural Highlands, Russia. In: Nagy, L., Grabherr, G., Körner, C. and Thompson, D.B.A. (Eds.) Alpine Biodiversity in Europe. Ecological Studies (Analysis and Synthesis), Vol. 167. Springer, Berlin–Heidelberg, p. 423–435.

Moiseev, P.A., Bartysh, A.A. and Nagimov, Z.Y. 2010. Climate changes and tree stand dynamics at the upper limit of their growth in the North Ural Mountains. *Russian Journal of Ecology* 41: 486–497. https://doi.org/10.1134/S1067413610060056.

Montesano, P.M., Nelson, R.F., Dubayah, R.O., Sun, G., Cook, B.D., Ranson, K.J.R., Næsset, E. and Kharuk, V. 2014. The uncertainty of biomass estimates from LiDAR and SAR across a boreal forest structure gradient. *Remote Sensing of Environment* 154: 398–407. https://doi.org/10.1016/j.rse.2014.01.027.

Olsson, R. 2009. Boreal Forest and Climate Change. *Air pollution and climate series* 23, Air Pollution and Climate Secretariat (AirClim) and Taiga Rescue Network, Göteborg, Sweden, 32 pp. Available online at: https://www.airclim.org/sites/default/files/documents/APC23_borealforest_0.pdf.

Othmani, A., Lew Yan Voon, L.F.C., Stolz, C. and Piboule, A. 2013. Single tree species classification from Terrestrial Laser Scanning data for forest inventory. *Pattern Recognition Letters* 34: 2144–2150. https://doi.org/10.1016/j.patrec.2013.08.004.

Parresol, B.R., Scott, D.A., Zarnoch, S.J. et al. 2017. Modeling forest site productivity using mapped geospatial attributes within a South Carolina Landscape, USA. *Forest Ecology and Management* 406: 196–207. https://doi.org/10.1016/j.foreco.2017.10.006.

Pogrebnyak, P.S. 1968. General forestry. *Kolos*, Moscow, 440 pp. (in Russian).

Pogrebnyak, P.S. 1955. Fundamentals of forest typology. Publishing house of the Academy of Sciences of the Ukrainian SSR, Kiev, 452 pp. (in Russian).

Ponomarev, E., Kharuk, V. and Ranson, K. 2016. Wildfires Dynamics in Siberian Larch Forests. *Forests* 7: 1–9. https://doi.org/10.3390/f7060125.

Ray, D. and Broome, A. 2001. Ecological Site Classification – supporting decisions from the stand to the landscape scale. In: Forest Research Annual Report 2001-2002. The Stationery Office, Edinburgh, p. 40–49.

Rich, P.M. and Fu, P. 2000. Topoclimatic Habitat Models. In: 4th International Conference on Integrating GIS and Environmental Modelling (GIS/EM4): Problems, Prospects and Research Needs. Banff, Alberta, Canada, p. 1–14.

Ryzhkova, V.A., Korets, M.A. and Danilova, I.V. 2009. Mapping of forest cover on the basis of genetic typology using GIS. In: Sannikov, S.N., Shavnin, S.A., Petrova, I.V. and Usoltsev, V.A. (Eds.) Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 184–187 (in Russian with English abstract).

Ryzhkova, V., Danilova, I. and Korets, M. 2011. A GIS-Based Mapping and Estimation the Current Forest Landscape State and Dynamics. *Journal of Landscape Ecology* 4: 42– 54. https://doi.org/10.2478/v10285-012-0033-0.

Sannikov, S.N. 1970. About ecological series of renewal and development of forest phytocoenosis within the forest types. In: Kolesnikov, B.P. (Ed.) Forest-forming processes in the Urals. Proceedings of the Institute of Plant and Animal Ecology, Vol. 67. The Ural Branch of the Academy of Sciences of the USSR, Sverdlovsk, p. 175–181 (in Russian).

Sannikov, S.N. 1974. About the principles of constructing series of climatically replacing forest types. *Russian Journal of Ecology* 1: 5–12.

Sannikov, S.N. 2009a. Divergence, convergence and inheritance of the structure of forest biogeocenoses. In: Sannikov, S.N., Shavnin, S.A., Petrova, I.V. and Usoltsev, V.A. (Eds.) Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 56–61 (in Russian with English abstract).

Sannikov, S.N. 2009b. Role of fires in the relationship between pine and spruce. In: Sannikov, S.N., Shavnin, S.A., Petrova, I.V. and Usoltsev, V.A. (Eds.) Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 133– 136 (in Russian with English abstract).

Sannikov, S.N., Sannikova, N.S. and Petrova, I.V. 2012. Outlines of theory of forest populational biology. Botanical Garden of the Ural Branch of the Russian Academy of Sciences, Yekaterinburg, 272 pp. (in Russian with English abstract).

Sannikov, S.N., Sannikova, N.S., Petrova, I.V. and Shavnin, S.A. 2014. Development of forest population biology and biogeocoenology in the Urals. *Siberian Journal of Forest Science* 3: 9–24.

Sedikh, V.N. 2009. Age dynamics of dark coniferous forests of Western Siberia. In: Sannikov, S.N., Shavnin, S.A., Petrova, I.V. and Usoltsev, V.A. (Eds.) Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 90–93 (in Russian with English abstract).

Sedikh, V.N. 2005. Landscape-typological basis for forest inventory in Siberia. *Lesnaya taksatsia i lesoustroistvo* 1: 70–77 (in Russian).

Shalaumova, Y.V., Fomin, V.V. and Kapralov, D.S. 2010. Spatiotemporal dynamics of the Urals' climate in the second half of the 20th century. *Russian Meteorology and Hydrology* 35: 107–114. https://doi.org.10.3103/S1068373910020044.

Shiyatov, S.G. 1993. The upper timberline dynamics during the last 1100 years in the Polar Ural Mountains. In: Frenzel, B., Eronen, M. and Glaser, B. (Eds.) Oscillations of the alpine and polar tree limits in the Holocene. Gustav Fischer Verlag, Stuttgart, Jena, New York, p. 195–203.

Shiyatov, S.G. and Mazepa, V.S. 2015. Contemporary expansion of Siberian larch into the mountain tundra of the Polar Urals. *Russian Journal of Ecology* 46: 495–502.

Shiyatov, S.G., Terent'ev, M.M. and Fomin, V.V. 2005. Spatiotemporal Dynamics of Forest–Tundra Communities in the Polar Urals. *Russian Journal of Ecology* 36: 69–75.

Shiyatov, S.G., Terent'ev, M.M., Fomin, V.V. and Zimmermann, N.E. 2007. Altitudinal and horizontal shifts of the upper boundaries of open and closed forests in the Polar Urals in the 20th century. *Russian Journal of Ecology* 38: 223–227.

Shorohova, E., Kuuluvainen, T., Kangur, A. and Jõgiste, K. 2009. Natural stand structures, disturbance regimes and successional dynamics in the Eurasian boreal forests: a review with special reference to Russian studies. *Annals of Forest Science* 66: 201p1–201p20. https://doi.org/10.1051/forest/2008083.

Smagin, V.N. 1973. Actual problems of forest typology. In: Issues of forest science, Vol. 2. Institute of Forest and Timber, Krasnoyarsk, p. 15–26 (in Russian).

Smolonogov, E.P. 1970. Usage of dimension of trees in stands in the diagnosis of forest types. *Russian Journal of Ecology* 1: 50–59.

Smolonogov, E.P. and Trusov, P.F. 1970. Variability of tree sizes in stands as an indicator of differences between forest types in mountain dark coniferous forests of the Northern Urals. *Russian Journal of Ecology* 4: 25–29.

Smolonogov, E.P. 1995a. Forest-forming process and genetic classification of forest types. *Lesa Urala i khoziyastvo v nikh* 18: 45–58 (in Russian).

Smolonogov, E.P. 1995b. Comprehensive zoning of the Urals. *Lesa Ural i Khoziyastvo v nikh* 18: 24–42 (in Russian).

Smolonogov, E.P. 1998. Main principles of the genetic approach to the typological classification of forests. *Russian Journal of Ecology* 29: 220–225.

Sochava, V.B. 1961. Issues of vegetation classification, typology of physical and geographical facies and biogeocoenosis. Vegetation classification and geobotanical cartography. In: Gorchakovskiy, P.L., Kolesnikov, B.P. and Sochava, V.B. (Eds.) Proceedings of the Institute of Biology, Vol. 27. The Ural Branch of the Academy of Sciences of the USSR, Sverdlovsk, p. 5–22 (in Russian).

Soloviev, V.M. 2009. Problems of the dynamic classification of stands in forest types. In: Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 65–68 (in Russian with English abstract).

Sukachev, V.N. 1957. The development of forest typology in the USSR over 40 years. In: Sukachev, V.N. and Nikitin, P.V. (Eds.) Progress in forestry over 40 years. Goslesbumizdat, Moscow–Leningrad, p. 5–16 (in Russian).

Sukachev, V.N. 1972. Fundamentals of forest typology and forest biogeocenology. Vol. 1. Nauka, Leningrad, 454 pp. (in Russian).

Tansley, A.G. 1935. The Use and Abuse of Vegetational Concepts and Terms. *Ecology* 16: 284–307. https://doi.org/10.2307/1930070.

Tsvetkov, V.F. 2009. Types of forest phytocoenosis formation as representative series of forest type dynamics. In: Sannikov, S.N., Shavnin, S.A., Petrova, I.V. and Usoltsev, V.A. (Eds.) Genetic typology, dynamics and geography of Russian forests. The Ural Branch of the Russian Academy of Sciences, Yekaterinburg, p. 69–71 (in Russian with English abstract).

White, J.C., Wulder, M.A., Varhola, A., Vastaranta, M., Coops, N.C., Cook, B.D., Pitt, D.G. and Woods, M. 2013. A best practices guide for generating forest inventory attributes from airborne laser scanning data using the area-based approach. *Forestry Chronicle* 89: 722–723.

Wulder, M.A. and Seemann, D. 2003. Forest inventory height update through the integration of lidar data with segmented Landsat imagery. *Canadian Journal of Remote Sensing* 29: 536–543. https://doi.org/10.5589/m03-032.

Zhabyko, E.V. 2013. Using the indicator groups of species for the classification of plant communities in Ussuriiskii natural reserve. In: Rosenberg, G.S. (Ed.) Modern botany in Russia. Proceedings of the XIII Congress of the Russian Botanical Society and Conference "Science behind the protection and wise use of vegetative cover of the Volga basin", Vol. 2. 'Kassandra', Togliatti, p. 216–217 (in Russian with English abstract).