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International Institute for Applied Systems Analysis • A-2361 Laxenburg • Austria
Tel: +43 2236 807 • Fax: +43 2236 71313 • E-mail: info@iiasa.ac.at • Web: www.iiasa.ac.at

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Classification of Russia's Forests in Relation to Global Climate Warming

Vladimir Stolbovoi (stolbov@iiasa.ac.at)

Approved by
Sten Nilsson (nilsson@iiasa.ac.at)
Leader, *Forest Resources Project*

Contents

Abstract

This study involves investigating the sensitivity to temperature of Russia’s forest communities. Factors taken into consideration were mean annual temperature; standard deviation and temperature tolerance limits covering forests across the country. A new numerical classification of forest, related to predicted global climate warming (GCW) has been developed based on cluster analyses.

New temperature-forest associations have been interpreted in order to develop a framework for the adaptation strategy to a predicted GCW. Quantitative parameters of the classification allow for the assessment of the magnitude, spatial and temporal dynamics of the GCW affect on forests. As a result, it is suggested that developed classification in forest inventory and management systems should be introduced in Russia.

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Classification of Russia's Forests in Relation to Global Climate Warming

Vladimir Stolbovoi

1. Introduction

The method of classification comprises various options designed to characterize and group the objects. This process results in the introduction of classes relevant to either scientific or practical tasks. This descriptive definition outlines the dual aspects of a classification, representing both the method and ultimate result that are regarded as the major domains of any study. According to several theoretical analyses (Lubistchev, 1982; Rozhkov *et al.*, 1990; Sokal and Sneath, 1963) the conclusion has been drawn that the amount of classifications should agree with that of the tasks, and probably (due to the diversity of the research aspects) in fact exceed these tasks. In reality, any classification can only be useful if measured by how appropriate it is for the purpose for which it has been established. The classification that has been distinguished for one task may therefore fail to suit the others.

The development of the approach to land evaluation serves to illustrate our concerns. This approach started from a general land suitability appraisal (FAO, 1976) dealing with the classification of land qualities for general purposes, i.e., rain-fed or irrigated agriculture (FAO, 1983; FAO, 1985). Later on, it was extended to include land evaluation for very concrete and specific land assessments (FAO, 1993). These classifications characterize the same plot of land using different criteria, but with the intention of reaching a level of consistency within the field of an agronomic knowledge base, and to properly meet specific crop requirements. However as researchers have adapted the existing classification schemes to suit new tasks, this is no longer likely to be the case. This also seems to apply when analyzing the GCW effect on the northern forests.

Generally, the prediction of the effects of the GCW on the boreal forests is based on the climate-forest associations that are traditionally known as bio-climatic regularities (belts, zones, sectors, vertical zones, etc.). These regularities have been investigated since the middle of the XIX century when Gumbold firstly recognized the principle of geographical zones. Since that time, numerous research projects have concentrated on establishing climatic–vegetational relations that are based on a wide philosophical concept of natural units. It is important to note that the major problem in implementing this idea originates from the disparity between recognizable vegetation patterns that are visually observed, mapped and relatively stable in space and time, and those climate parameters that are randomly recorded and highly variable (yearly, seasonally, spatially). There has been an attempt to overcome this data inconsistency between two phenomena, namely biosphere and atmosphere, through the positioning of vegetation communities within climate parameters. Numerous researchers have concentrated on recognizing direct climate characteristics, (solar radiation, temperature, precipitation and so on) or indirect ones (humidity, aridity, continentally, evapotranspiration coefficients, etc.), which are highly correlated with the boundaries of the vegetation communities. This knowledge has been put to good use by climatologist (Alisov, 1956; Köppen, 1936; Thornthwaite, 1948) for the purposes of climate classifications. Pedologists and geographers (Budyko, 1974; Dokuchaev, 1951; Grigoriev and Budyko, 1956; Hunt, 1974.) utilized it for elaboration of soil and landscape hierarchy. Ecologists and botanists (Archibold, 1995; Bailey, 1996; Bailey 1998; Holdridge, 1967; Olson and Watts, 1982; Tansley, 1935; Woodward, 1987) used it to establish climatic–vegetational units. The knowledge about the climate–vegetation associations has also been implemented in terrestrial models (i.e., Climate Change, 1996; Prentice *et al.*, 1992, 1993) intended to predict the GCW effects on terrestrial ecosystems. The approach is based on the assumption that expected GCW will drive vegetation changes accordingly. Although this so-called “climate envelopes approach” (Henderson-Sellers, 1994) has been heavily criticized for oversimplification, it is presently the only concept proposed to replace the one present in the GCW studies. Luckman and Kavanagh, 1998, have documented that the local heterogeneity of vegetation responses is more divergent than comparing ecotone to climate variability. From our point of view, ignoring heterogeneity response results from a research approach that is too narrowly oriented, and also concentrating too much on the establishment of border parameters for climatic–vegetational associations. This method does result in a stagnation of knowledge.

The problem does exist of how relevant traditional climate-vegetation patterns, i.e., belts, zones, climate niches, life zones, etc., are to the GCW specific research task. It stems mainly from the fact that in spite of tremendous efforts and application of heavy tools, many critical questions have not yet been clearly answered. This includes that of integrated modeling (Prentice *et al*., 1992, 1993). Some of these questions are the following: What will be the magnitude of the GCW effect? How will it spread over time and space? What should forest management do to identify its effects and to adapt to the predicted GCW? We consider one of the key questions that must be addressed is how the concept of natural units applies with respect to the GCW issue.

The overall goal of the present study is to investigate how forests depend on temperature and based on that premise, to develop a new classification of boreal forests, which will be relevant to the issue of GCW[1]. An attempt has also been made to propose some easily accessible and widely available climate parameters to be used to establish this classification. The research is intended to identify basic criteria and indicators that allow the prediction of forest behavior and to develop an adaptive strategy to meet expected GCW.

2. Methods and Results

The study is based on broad GIS analyses of vegetational and climatic geo-referenced databases within an integrated land information system of Russia. The system has been developed though the joint efforts of numerous organizations under leadership of IIASA. These include FAO, the Dokuchaev Soil Institute, the All-Russia Institute of Forest Resources and others. The GIS tools are applied to investigate the dependence

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[1] We simplify GCW as a complex integrated concept for temperature changes. The level of uncertainty increases when only few factors are taken into consideration. It is also important to note that we are working within a forest zone where the precipitation factor is not as critical as it is within traditional research of forest-non-forest boundaries.

of temperature on appearance of the forest. As far as we are able to ascertain, this is the first time that such an analysis has been implemented in Russia. Technically, we used 5x5 km terrestrial grids with attributes of temperature (Leemans *et al*., 1991) and of vegetation (Stolbovoi *et al.*, 1998). These analyses allowed for the establishment of upper and lower temperature limits, the mean annual temperature and its standard deviation applicable to all forest communities throughout the country. These parameters have been introduced as the main criteria in order to classify forests relevant to the GCW impacts.

The forest terminology has been drawn from the description of the vegetation database (Stolbovoi *et al*., 1998). At the scale of the investigation (1:4 million) the territory of Russia comprises 48 forest vegetational communities. Traditionally, they are classified by different classes. These include dominant tree species, such as dark and light coniferous, broad-leaved forests; bio-climatic features grouped into pre-tundra open woodland (forest-tundra); northern, middle, southern taiga[2] and subtaiga forest steppe-zones and sub-zones; relief peculiarities (both plains and mountains); and antropogenic impact (primary and secondary forests).

According to the database, 58% of the total area — or more than 650 million ha. is covered with plain forest and it represents an entire range of boreal bio-climatic lateral forest zones. The latter regularly changes within two dimensions: from north to south following an improvement of the heat provision of plants, and from west to east reflecting changes of continental climate, which also manifests the adaptability and survival ability of various wood species.

Mountain forest extends over 480 million ha, comprising about 42% of the country’s total forests. These regions introduce well-developed spectrums of vertical bio-climatic belts that manifest regular changes of the forest species depending upon two factors: (1) the temperature decrease with the increased elevation and; (2) heating capacity of the slopes according to various levels of exposures. The bio-climatic differentiation exposure is common in the continental climate of East Siberia where high air pressure prevents the local circulation of air masses. This results in extremely contrasting temperature regimes, depending on the amount of the direct solar radiation available to the site; i.e., steppe-type vegetation might exist alongside tundra

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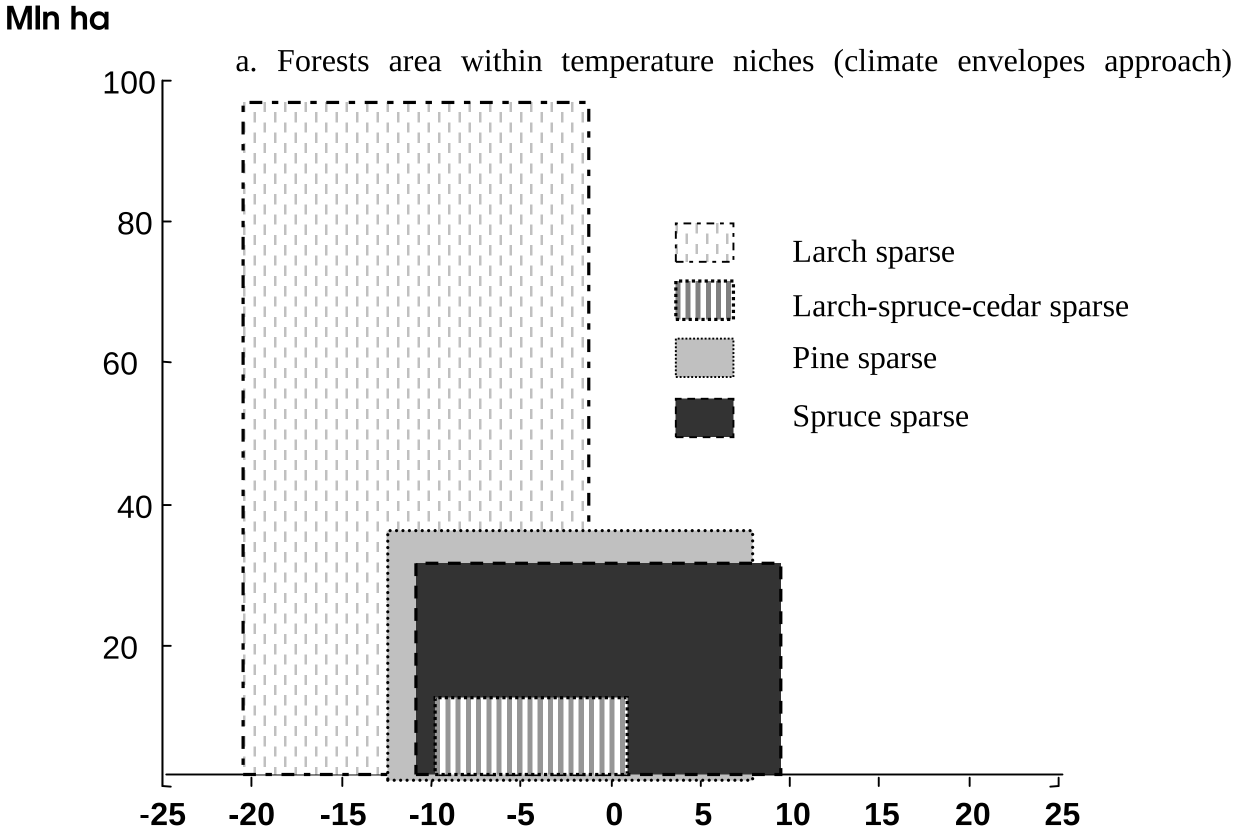
[2] Dark (spruce, fir, cedar) and light (larch, pine) coniferous boreal forest of the temperate belt of the northern hemisphere.

vegetation. The vertical spectrum of forest belts generally resembles those of the latitudinal vegetation zones moving northward.

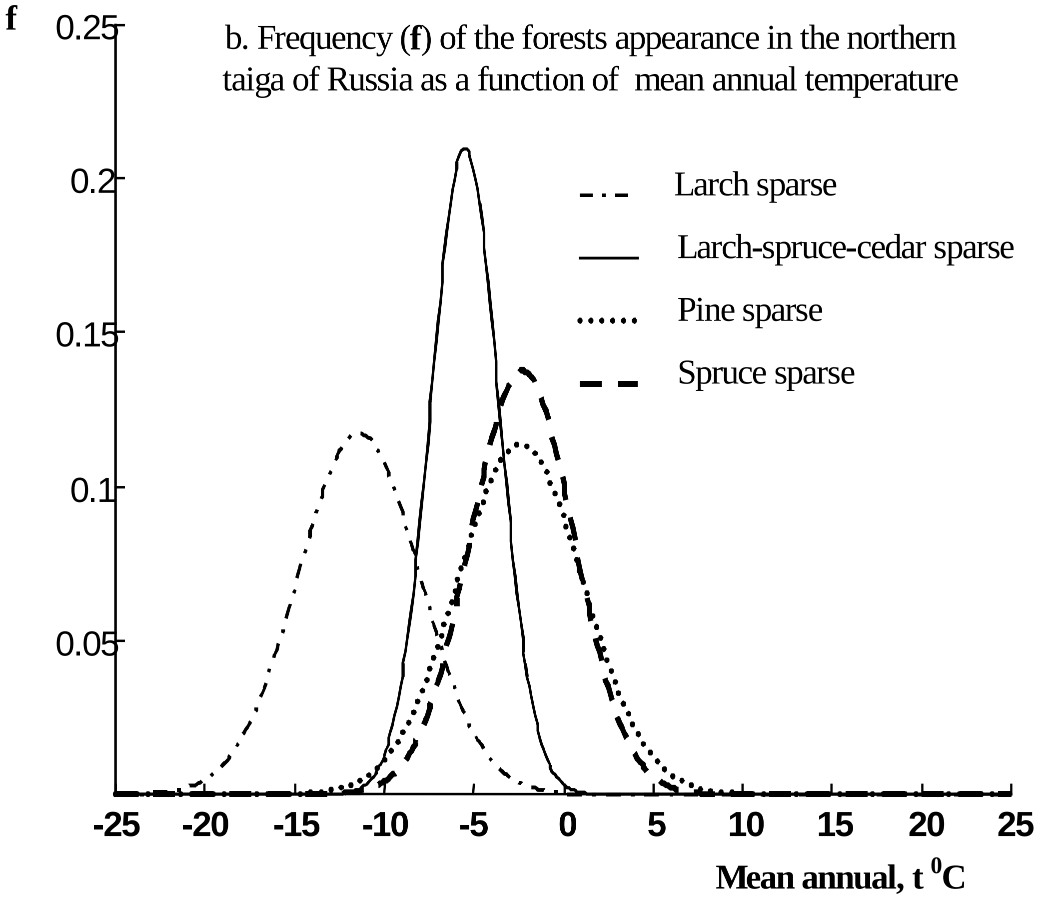
The basic geographical and ecological sciences (Bailey, 1998; Budyko, 1974; Holdridge, 1967; Odum, 1971; Tansley, 1935) suggest that bio-climate regularities do drive both surface geosphere (weathering and geo-chemical processes) and biosphere (photosynthesis and biomass accumulation) development. These environments have been transformed over a long period, attempting to approach a thermo-dynamic equilibrium with the atmosphere, and to reach a harmony in the geosphere — which is often regarded as a climax (Meeker and Merkel, 1984). This schematic consideration can be illustrated by *Figure 1a*, where the temperature-forest associations are shown for the northern taiga of Russia and assumed to be in equilibrium with their thermal conditions. According to *Figure 1a*, the temperature-forest interrelation is a simple functional dependence, and forests within "climate envelopes" have been distributed homogeneously. Applying this scheme to the GCW issue proposes that the change of temperature limit will consequently result in a shift of the forest communities. Clearly, this assumption ignores the real forest spatial distribution. It also tends to simplify some basic ecological and physiological fundamentals. In fact, forest — similar to any other biological object — displays its preferences to site conditions. Forests form spatial heterogeneity according to the site selection in such way that they concentrate on more favorable conditions. This evidence is also true for forest productivity and the accumulation of biomass. To overcome this shortcoming we must introduce a more reliable form of analysis and look inside "climate envelopes" to investigate the forest heterogeneity.

The frequency of forest dependence on temperature for the northern taiga forests is shown on the *Figure 1b*. It can be observed that the distribution of the temperature-forest associations is considerably different from that indicated in *Figure 1a*. The shape of the curves has little common with "climate envelopes" shown in the form of square boxes. The distribution is a Gaussian normal distribution, which can be observed for most randomly sampled characteristics of the natural objects. In addition to the limits based on temperature niches (the boxes based on *Figure 1a*), mean annual temperature and its standard deviation can also characterize the forests under consideration. These two parameters appear to be very important for forest classification related to GCW.

Figure 1. Temperature-forest associations of the northern taiga of Russia.



a. Forests area within temperature niches (climate envelopes approach)



b. Frequency (**f**) of the forests appearance in the northern taiga of Russia as a function of mean annual temperature

Mean annual temperature corresponds well to the high frequency of forest appearance associations. It identifies the temperature around which the forest population has the highest density. The latter consequently decreases when moving towards cool and warm temperature limits occurring in the community. The degree of the mean annual temperature also provides a clearer understanding of the thermal behavior, and the interactions between various forest communities of the northern taiga. *Figure 1b,* for example, shows that a sparse mix of larch-spruce-cedar forest occupies the intermediate thermal position between the warmest part of the sparse larch forest and the coolest parts of the sparse spruce and pine forests.

Standard deviation of the mean annual temperature will identify the compactness of the forest spatial distribution, and this could be established as a definite measurable indicator of the sensitivity of the forest to GCW. For example, a comparison of the temperature change of the sparse larch-spruce-cedar forest — for which standard deviation of the mean annual temperature is 1.9^0C — with those of the sparse larch sparse forest, which has a standard deviation of 4.2^0C.

The differences of forest-thermal behavior and, consequently, on responses to temperature change depend upon the position of the forest community within a certain temperature niche. This is described well (see *Figure 2*) by the mean annual temperature, and statistically it identifies the cool and warm limits of forests. The GCW will cause a heat stress and will even lead to forest replacement where the increased temperature will exceed statistical upper thresholds. It will probably result to a thinning of the natural forest. At the same time, the cooler areas of the same forest community will benefit from the warming and experience improved growing conditions. Some forest interventions might also be expected on neighboring territories, which before the GCW had temperatures below the lowest statistical temperature threshold of forest occurrence. Eventually, this expansion is associated with a very specific phenomenon of a northward shift of the forest. (Zinyowera *et al*., 1996). The above information leads us to conclude that forest responses to GCW — even within a single forest community — will be substantially diverse. This is in line with some recent findings (Luckman and Kavanagh, 1998; Peterson, 1998), and is illustrated by *Figure 1b*, indicating shifts in the magnitude of around -5^0C. Where this temperature change occurs, the sparse larch sparse forest will be strongly affected by heat stress. Conversely, sparse spruce and pine forests will improve their thermal behavior. Lastly, sparse larch-spruce-cedar forest will probably react indifferently to this change, and more focus will be placed on this detail below.

The dependence of the frequency of forest appearance as a function of temperature can be used to describe the response of forest to the GCW. As mentioned above, this function is likely to be a Gaussian distribution that is $N(t_0\,\sigma)$ with a mean annual value t_0 and with a standard deviation $\sigma > 0$ (*Figure 2*).

It is realistic to identify a temperature range $[t_0\text{-}T,\ t_0\text{+}T]$ within which almost all forests occur. For instance, if $T \pm 3\ \sigma$, more than 97% of the forests belong to this interval[3].

These relations make it possible to establish different forest-response segments related to predicted GCW, i.e., to estimate the dynamics of the forest area that will be replaced due to temperature increases. The calculation is rather simple and has been described well in mathematical statistics textbooks. The easiest application of this calculation is to assume a gradual reduction of the forest area, which is caused by and increase in temperature.

For that situation, let the temperature upper limit increase by $t\Delta$, whereby the forest that is indicated by the arrow (*Figure 2*) could not survive because it will fall outside the upper limit of temperature tolerance. The reduced segment of the forest area can be calculated by the following standard equation:

$$\int_{to-T}^{to+T-\Delta t} f(t)dt = \frac{1}{\sqrt{2\pi\sigma}} \int_{-T}^{T-\Delta t} \exp(-\frac{x^2}{2\sigma^2})dx = \frac{1}{\sqrt{2\pi}} \int_{\frac{-T}{\sigma}}^{\frac{T-\Delta t}{\sigma}} \exp(-\frac{u^2}{2\sigma^2})du =$$

$$\begin{cases} f(\frac{T}{\sigma}) + f(& \text{if } T = t\Delta \\ f(\frac{T}{\sigma}) - f(& \text{if } T < t\Delta, \end{cases}$$

where

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_0^x \epsilon^{x=0}$$

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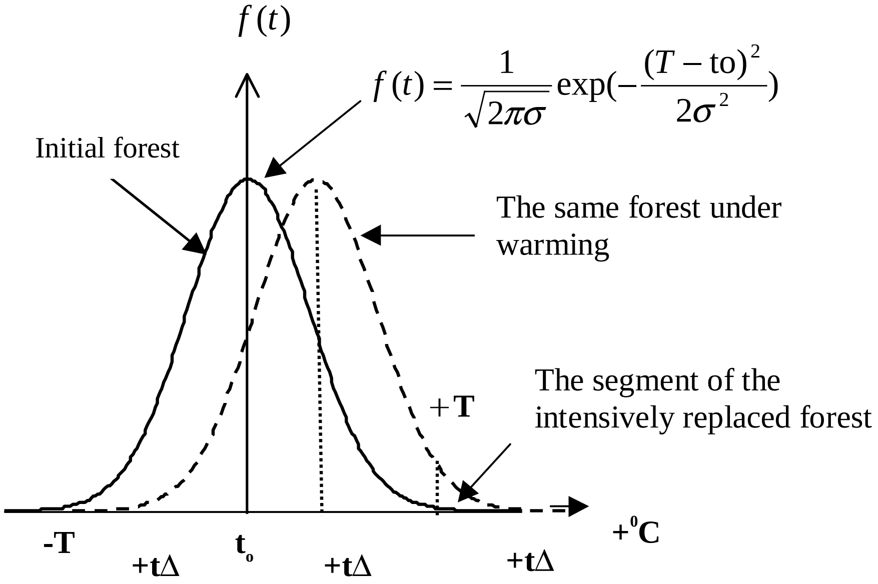
[3] This value corresponds to the accuracy of our database.

Figure 2. Forest in temperature shifts



t_o - mean annual; +T – mean maximum; -T – mean minimum;
+tΔ - temperature increase

An increase of temperature by 1σ might cause replacement of about 1% of the forest community area. Consequently, if the GCW occurs at the level of 2σ, the area of the forest replacement will be around 17% of the total forest community, etc. This equation easily facilitates estimating various temperature effects on areas and segments of a particular forest community.

As suggested above, 97% of any forest communities existing in the temperature niche t_0±3σ, gives a temperature tolerance interval equal to 6σ. It is reasonable to apply the value of standard temperature deviation of mean annual temperature to define segments of the temperature-forest response classes (*Figure 3*). It seems logical to distinguish forest occurring in the thermal conditions of around mean annual temperature (t_0±σ) as segments of indifferent responses to GCW. We assume that this forest segment is adapted to the yearly temperature variability and therefore, will not immediately response to a temperature increase. According to the Gaussian distribution, the segment responding indifferently occupies about 67% of the forests. These forests appear to behave similarly to mature forests and manifest a normal successional development.

Forest segments (*Figure 3*) occurring within the interval from ($t_0 \pm 2\sigma$) to ($t_0 \pm \sigma$) will pose different responses to GCW. A moderately positive effect could be expected in forests where growing conditions will be improved by temperature increase. This will happen in the forest segments occurring under conditions below mean annual temperature in the interval from ($t_0-\sigma$) to ($t_0-2\sigma$). This forest segment can be identified as having increased growing activities, but with normal forest development. A highly positive effect can be expected on the forest occurring within the temperature niche from ($t_0-2\sigma$) to ($t_0-3\sigma$), where very intensive forest growth will occur.

Where temperature increases will cause increased heat stress, a moderately negative effect (*Figure 3*) can be expected by the GCW. It is likely that this effect will be found in the forest segment occurring in the conditions above mean annual temperature within the interval from ($t_0+\sigma$) to ($t_0+2\sigma$). These forests can have appearance of successions that are not typical for existing forests. Forests occurring in the temperature interval from ($t_0+2\sigma$) to ($t_0+3\sigma$) are assumed to have clear symptoms of replacement. This can be concluded from the occurrence of over-matured stands without forest undergrowth, and the appearance of the successions not usual for the existing forest community.

A numerical classification matrix has been created by means of cluster analyses of the combination of mean annual temperature and its standard deviation. The forest communities of Russia have been sorted according to their temperature characteristics (*Figure 4*). Following this procedure five temperature-forest groups have been distinguished. They are:

- *Very cool* boreal forest with mean annual temperature less than -6^0C.
- *Moderately cool* boreal forest with a mean annual temperature range from -6 to -2^0C.
- *Cool* boreal forest with annual mean temperature limits from -2 to $+2^0$C.
- *Slightly warm* boreal forest with temperature range from $+2$ to $+6^0$C; and
- *Warm* boreal forest with temperature more than $+6^0$C.

Figure 3. Temperature-response segments (% of community).

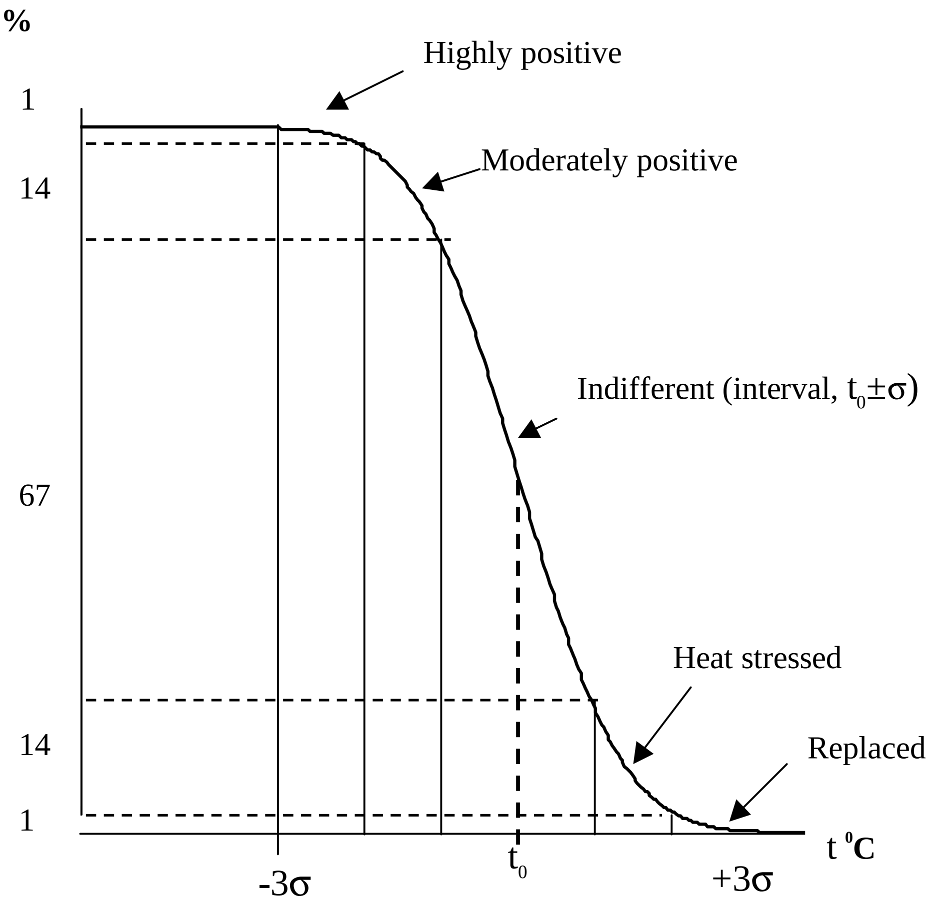


Figure 4. Distribution of forest communities within a combination of the mean annual temperature and its standard deviation

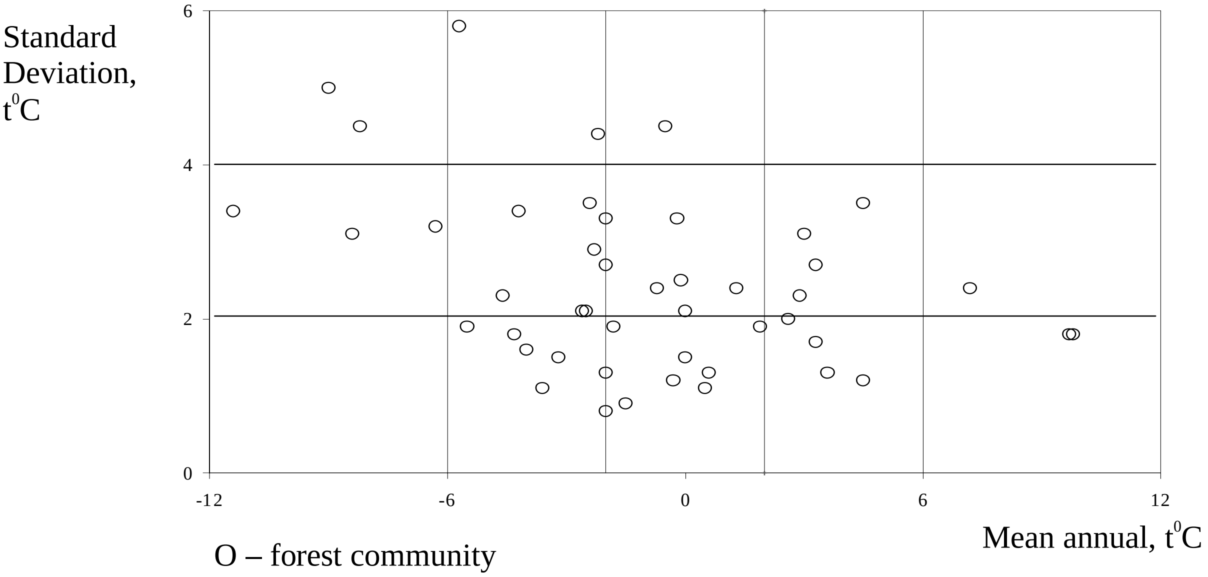


Figure 4 indicates that most forest communities occur in the temperature range of between –6 to +6^{0}C. Thus, Russian boreal forests may be classified as ‘cold’. This also assumes that these forests have a high ability to adapt to cold climates (Levitt, 1980; Odum, 1971).

Forest communities in the country (*Figure 4*) are grouped into three classes according to standard deviation of mean annual temperature. They are:

- *Slightly sensitive* to temperature change with the standard deviation of more than 4^{0}C.
- *Sensitive* to temperature change with a standard deviation varying from 2 to 4^{0}C.
- *Highly sensitive* to temperature change with a standard deviation less than 2^{0}C.

The forest sensitivity to temperature change (*Figure 4*) is lower for the very cool, and higher for the warm boreal forests, i.e. there are no highly sensitive forests for temperatures less than –6^{0}C. The same applies to slightly sensitive forest temperatures of more than +6^{0}C. This fact corresponds well with the fundamental ecology, which is abstractly illustrated in *Figure 3*. The effect of a rise in temperature will reach maximum impact in the warm segments of the forest community, where it may even cause forest replacement due to heat stress. The forest growth is expected to increase in the cool forest segment, where a deficit temperature exists. Applying this consideration to the terrestrial ecosystem, this suggestion is in line with the common opinion (Bazilevich, 1993; Zinyowera *et al.*, 1996) that GCW will cause higher productivity increases in the northern regions, compared to those in the south.

The temperature-forest associations of Russia, which are characterized by mean annual temperature, temperature upper and lower limits (thermo-tolerance) and standard deviation of mean annual temperature are presented in *Table 1*. It is therefore possible to propose three temperature-forest taxonomic units related GCW:

- *Class* — identifies basic temperature-forest niches of Russia’s forest communities. They are diagnosed by combining mean annual temperature and main forest forming species. These combinations indicate the major trajectories of the forest change, according to the assumed GCW and allow for the prediction of the impacts. This provides a foundation of basic information necessary to select strategies for reforestation and afforestation, selection of tree species, etc.

- *Type* — corresponds to the sensitivity of the forest community to temperature change. They are diagnosed by the temperature tolerance intervals and the composition of the forest community in terms of prevailing monodominant or polydominant (mixed) forest. This information is valuable for establishing a proper forest management regime in close harmony with natural development patterns.
- *Genus* — refers to the forest thermal behavior segments within a forest community. They are diagnosed by the value of standard deviation of mean annual temperature, and by succession structure of the forest community. This information is important to establish site specific adaptation strategies.

Based on the criteria mentioned above all forest communities of Russia have been classified accordingly (*Table 1*).

3. Discussion and Conclusions

The new proposed classification of the temperature-forest associations is very different from traditional bio-climatic schemes of the boreal forest in Russia. Classes related to the GCW combine forest of different zones and reliefs. They identify separate same zone and subzone forest communities and record their relevance to temperature changes. *Table 1*, for example incorporates larch forests in a traditional bio-climatic scheme (Stolbovoi *et al*., 1998) into different vegetation zones, pre-tundra open woodland, northern and middle taiga. Thus classified, they are placed in one type of the cool boreal forest that is sensitive to the temperature. At the same time, sparse larch forest and sparse spruce forest that are included in one plain northern taiga subzone are classified in different thermal classes and sensitivity types. The differences between traditional and proposed classifications more or less illustrate the general statement above that common bio-climatic classes can hardly meet the requirements of classification of forests related to GCW.

Analyses of the temperature-forest niches (*Table 1*) recognize that very cool boreal forest combines monodominant larch forests of several plain bio-climatic zones from the pre-tundra open woodland in the north, to the middle taiga zone in the south. It also includes pine (*Pinus pumila)* with larch open woodlands, tundra and dark coniferous forests in mountain subgoltsy open woodlands. Due to the broad thermo-tolerance of these forests they can be slightly sensitive, or indeed sensitive to the change in temperature. Several authors (Graumlich *et al.*, 1989; Peterson, 1994) have already found that an increase the tree growth of cool boreal forest can be expected according to the predicted GCW. This would include some limited expansion of the pine forests, to the cost of the larch forest.

It is worth noting that the major part of these forests are natural (frontier) and very scarcely investigated by on-the-ground methods. There is therefore little use in proposing any management or any particular site specific strategies for utilization.

The warmest forests are predominantly represented by the mixed polydominant forests rather typical for the southern taiga of Russia. Climatological fluctuation of precipitation can be an explanation of the development of this forest in the south. According to Rode (1962) any climate is subject to short-term 11, 45, 90 years hydrological cycles. These fluctuations play an important role for forest that occurs in regions with a humidity coefficient (precipitation-evaporation ratio) close to 1.0. The humidity coefficient for the southern taiga subzone ranges from 1.3 to 0.7. The latter is reported for the Priangarje region in the south of East Siberia (Soil geographical regionalization of the USSR, 1962). The monodominant forest has no adaptation mechanism to allow it to adjust to the climate. This type of forest cannot survive successfully during a series of dry years when it prefers wet growing conditions. The opposite also applies. If the forest prefers to grow in dry environments it will suffer as a consequence of many years of wet climate. The mixed forests have the highest resilience capacity, and are the most adaptable to different climates. However, this consideration leads to the conclusion that a factor other than temperature, namely the precipitation pattern, will play a key role in possible expansion of mixed forests in the southern taiga subzone. This factor has not been considered in the present study.

The northern forest boundary[4] has been found in the very cool boreal forest and illustrated by the mean annual minimum temperature of –34.2^{0}C (Stolbovoi and Nilsson, 1998). However, as established earlier, the minimum winter air temperature does not directly control the position of the northern forest boundary[5]. This leads to the conclusion that other climate characteristics, i.e., continentally, air humidity, wind regime, etc., have to be introduced into the analysis in order to predict forest intervention possibilities to the north.

Considering the variety within forest zones and subzones (*Table 1*) it is clear that the larch forest has always occupied the coolest locations in both plain and mountain taiga. The temperature niche distance between larch and other forests is so significant that it practically eliminates larch form any competition concerning 96% of Russia’s boreal forests. For example, in the pre-tundra zone, there is a difference of about 17^{0}C between the sparse larch and its closest ecological neighbor the sparse spruce forest. The difference between the larch and the cedar-spruce-fir forest in the southern taiga subzone is 8^{0}C. This allows the assumption that intervention to the north of the southern zones and subzones cannot be expected. It is more probable to assume that the GCW will cause an increase in the growth of larch forests. Possible expansion of pine forest at the cost of larch forest cannot be ignored. This process has been identified in many places where natural conditions become more favorable. We can also expect that the mixed coniferous forests will experience a slight northward expansion.

The southern forest boundary is assumed to have shifted to the north. There is an expectation that the steppe vegetation will expand northward at the cost of forested area. Based on the principle scheme (*Figure 2*) there does seem to be a high probability of this occurring. GCW will very effectively influence the forests

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[4] In scientific literature this boundary is traditionally associated with the term “northern tree line”, which, from our point of view is rather confusing. The term creates the feeling among those not familiar with these territories that there is an existing boundary ‘line’ between forest and tundra vegetation zones. Instead, the transition between them is very smooth, and the boundary is a matter of convention (Körner, 1998). Forest-tundra is the intermediate bioclimatic zone comprising something heterogeneous. Some dwarf larch trees penetrate far into the tundra as solitary trees. Sometimes they form separate groups of weakly developed trees that are surrounded by tundra. In turn, tundra vegetation is spreading southward and even reaches steppe zone in certain geomorphological locations. However, a precise boundary has never been recognized between forest and tundra vegetation, as it is in the case of the forest-steppe vegetational zone.

[5] Sparse larch forest of the northern taiga might occur even at lower mean annual minimum temperatures than those found in the pre-tundra zone. The temperature condition in the tundra is significantly warmer when compared with those of the forest-tundra, i.e., mean minimum temperature for arctic deserts is about –28^{0}C and for the continental plain tundra it varies from –23 to –32^{0}C.

occurring under conditions close to their upper temperature limits. It appears that in the long run, tree plants are unable to avoid heat stress even if there is a sufficient increase in the amount of precipitation to allow for adaptation processes.

The upper temperature limit (*Table 1*) for the plain boreal forest in Russia is 19.4^0C. This value has been recorded for pine forest (*Pinus sylvestris*) in the forest-steppe bio-climatic zone. It is important to note that mean maximum temperature limit of occurrence of forest occurrence in the country is about 20.8^0C. This has been observed in temperate broad-leaved forests. The conclusion can also be drawn that these two numbers are very close (the difference is only 1.4^0C). It is therefore to be expected that both forest types will be equally strongly affected by GCW. More attention has to be paid to the forest responses on the southern forest boundary, where intensive forest transition has been identified.

The results of the study can be summarized as follows:

1. A new temperature-forest classification for Russia has been developed. This classification is considerably different from that of the traditional bio-climatic classification and classifies forests according to their thermal characteristics. The new classification introduces forest classes according to their major thermal features, sensitivity and responses to temperature changes. These classes are relevant to GCW. The implementation of the classification by forest inventory and management will allow for the development of adaptation strategies for the predicted GCW.
2. The frequency of forest appearance as a function of temperature follows a Gaussian distribution and thus, can be correctly described by mean annual temperature and its standard deviation. It is proposed that these characteristics are applied to determine the magnitude the impacts of GCW, and on their dynamic dependence on gradual temperature increases.
3. Projected GCW does not indicate an intensive intervention by the forests to the north. The most visible changes could be associated with transformations in the composition of the forest communities within zones and subzones. Improvement of the larch forests performance and an increase of the share of the mixed forests (to a limited extent) can also be identified. The southern forest boundary will probably experience more dramatic forest transitions resulting in forest areas being replaced by non-forest vegetation. In order to

predict this development some additional climatic parameters, i.e. wind, air humidity, snow cover, etc., must be analyzed. In must also be said that the scenarios for these parameters within the GCW studies are very uncertain, which makes forest response predictions rather provisional.

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Table 1. Classification of boreal forest of Russia related to global climate warming.

Temperature — forest niche	**Sensitivity to temperature change**	**Forest community**	**Temperature ^{0}C**		**Thermal (^{0}C) behavior segment**				
			Mean annual	σ	Replacing	Heat stressed	Indifferent	Moderately positive	Highly positive
Very cool boreal forest	Slightly sensitive	Sparse larch forest with low bush-moss and low bush-lichen cover. Plain, northern taiga.	-11.4	4.2	>-3.0	-.3.0 to -7.2	-7.2 to -15.6	-15.6-19.8	<-19.8
		Pine forest (*Pinus pumila)* with larch open woodland and tundra. Mountain, subgoltsy open woodland.	-9.0	5.0	>6.0	1.0 to -4.0	-4.0 to -14.0	-14.0 to -29.0	<-29.0
		Larch forest. Mountain, taiga.	-8.2	4.1	>4.1	4.1 to -4.1	-4.1 to -12..3	-12.3 to -20.5	<-20.5
	Sensitive	Larch forest with low bush-lichen-spruce cover. Plain, pre-tundra open woodlands	-12.2	3.3	3.3	-3.3 to -8.9	-8.9 to -15.5	-15.5 to -22.1	<-22.1
		Larch forest with low bush-moss-lichen cover. Mountain, subgoltsy open woodland	-12.2	3.5	>-1.7	-1.7 to -8.7	-8.7 to -15.7	-15.7 to -22.7	<-22.7
		Larch forest. Plain, middle taiga.	-8.4	3.1	>0.7	0.7 to -5.3	-5.3 to -11.5	-11.5 to -18.7	<18.7
		Dark coniferous with low bush-moss-lichen cover. Mountain, subgoltsy open woodland	-6.3	3.2	>3..3	3.3 to -3.1	-3.1 to - 9.5	-9.5 to -15.9.	<-15.9
Moderate cool boreal forest	Slightly sensitive	Shrub-coniferous sequence in river valleys.	-5.7	5.8	>11.7	0.1 to 11.7	0.1 to -11.5	-11.5 to 23.7	<-23.7
		Pine forest with low bush-moss and lichen cover. Plain, middle taiga.	-2.2	4.4	>11	2.2 to 11	2.2 to -6.6	-6.6 to -15.4	<-15.4
	Sensitive	Larch-spruce-cedar sparse forest (*Pinus sibirica, Picea obovata, Larix sibirica*) with low bush-lichen cover. Plain, northern taiga	-5.5	1.9	>0.2	0.2 to -3.6	-3.6 to -7.4	-7.4 to -11.2	<-11.2
		Cedar and fir-cedar forest (*Pinus sibirica, Abies sibirica* , *Larix sibirica, Picea obovata*) with low bush-short grass-moss cover. Mountain, taiga.	-4.6	2.3	>2.3	2.3 to -2.6	-2.6 to -6.9	-6.9 to -11.5	<-11.5

		Cedar-spruce and fir-spruce forest. Mountain, taiga.	-4.2	3.4	>6.0	6.0 to -0.8	-0.8 to -7.6	-7.6 to -14.4	<-14.4
		Larch (*Larix gmelinii*) and pine-larch forest with low bush-grass cover. Plain, southern taiga	-4.0	1.6	>0.8	0.8 to -2.4	-2.4 to -5.4	-5.4 to -8.8	<-8.8
		Spruce forest (*Picea obovata*) with mosaic low shrub-spruce cover. Plain, pre-tundra open woodland.	-3.6	1.1	>-0.3	-0.3 to -2.5	-2.5 to -4.7	-4.7 to -6.9	<-6.9
		Spruce-cedar and cedar-spruce forest (*Pinus sibirica, Picea obovata*) with grass-low bush-moss cover Plain, middle taiga	-3.2	1.5	>1.3	1.3 to -1.7	-1.7 to -4.7	-4.7 to -7.7	<-7.7
		Birch forest (*Betula lanata*) with high grass cover. Mountain, taiga.	-2.6	2.1	>3.7	3.7 to -0.5	-0.5 to -4.7	-4.7 to -8.9	<-8.9
		Spruce-fir and cedar-fir forest with grass-low bush cover. Mountain, taiga.	-2.5	2.1	>3.8	3.8 to -0.4	-0.4 to -4.6	-4.6 to -8.8	<-8.8
		Pine sparse forest with low bush-grass-lichen cover. Plain, northern taiga	-2.4	3.5	>8.3	1.1 to 8.3	1.1 to -5.9	-5.5 to -12.9	<-12.9
		Spruce sparse forest with *Betula nana* in low bush-lichen-grass cover. Plain, northern taiga	-2.3	2.9	>6.4	6.4 to 0.6	0.6 to -5.2	-5.2 to -11.0	<-11.0
		Shrub-small-leaf forests and steppe meadows in river valleys.	-2.0	3.3	>7.9	7.9 to 1.3	1.3 to -5.3	-5.3 to -11.9	-11.9
		Pine forest (*Pinus sylvestris*). Mountain, taiga.	-2.0	2.7	>6.1	6.1 to 0.7	0.7 to -4.7	-4.7 to -10.1	<-10.1
	Highly sensitive	Cedar-spruce-fir forest (*Abies sibirica, Picea obovata, Pinus sibirica*) with mosaic short grass-moss cover. Plain, southern taiga.	-2.0	1.3	>1.9	1.9 to -o.7	-0.7 to -3.3	-3.3 to -5.9	<-5.9
		Oak-hornbeam, hornbeam forest (*Carpinus betulus, Quercus robur*) with *Acer pseudoplatanus, Cerasus aviumm* Plain, broad-leaved forest.	-2.0	0.8	>0.4	0.4 to -1.2	-1.2 to -2.8	-2.8 to -4.4	<-4.4
Cool boreal forest	Slightly sensitive	Pine (*Pinus sylvestris*) and larch-pine forest with grass-moss (*Pinetum hylocomiosum*) and low bush-lichen-moss cover. Plain, southern taiga	-0.5	4.4	>12.7	12.7 to 3.9	3.9 to -4.9	-4.9 to -13.7	<-13..7
	Sensitive	Spruce-fir, cedar-fir, fir-spruce forest with nemorose elements Mountain, taiga.	-0.7	2.4	>6.5	1.7 to 6.5	1.7 to -3.1	-3.1 to -7.9	<-7.9

		Pine forest (*Pinus sylvestris*) with grass cover, frequently forest with pine and meadow-steppe species (southern bor) undergrowth and cover of nemorose species. Plain, subtaiga.	-0.2	3.3	>9.7	9.7 to 3.1	3.1 to -3.5	-3.5 to -10.1	<-10.1
		Oak forest. Plain, broad-leaved forest.	-0.1	2.5	>7.4	2.4 to 7.4	2.4 to -2.6	-2.6 to -7.6	<-7.6
		Spruce, fir-spruce and spruce-fir forest with mosaic grass-low bush and grass-moss cover. Plain, southern taiga.	1.3	2.4	>8.5	3.7 to 8.5	3.7 to -1.1	-1.1 to -5.9	<-5.9
		Cedar-broad leaved forest (*Quercus mongolica, Betula costata, Pinus koraiensis*). Piedmont and mountain.	0.0	2.1	>6.3	2.1 to 6.3	2.1 to -2.1	-2.1 to -6.3	<-6.3
	Highly sensitive	Larch forest (*Larix gmelinii*) with *Quercut mongolica*, *Betula davurica* and other grass species undergrowth and cover of nemorose species. Plain, subtaiga.	-1.8	1.9	>3.6	0.1 to 3.6	0.1 to -5.4	-5.4 to -7.2	<-7.2
		Birch forest (*Betula czerepanovii* with *Pinus sylvestris, Picea obovata*) with short grass-low bush and spruce cover. Plain, pre-tundra open woodland.	-1.5	0.9	>1.2	-0.6 to 1.2	-0.6 to -2.4	-2.4 to -4.3	<-4.3
		Shrub-small leaved forest sequence (*Betula pendula, Populus tremula, P.nigra, P.alba*) in river valleys.	-0.8	0.9	>1.9	0.1 to 1.9	0.1 to -1.7	-1.7 to -3.5	<-3.5
		Aspen-birch forest (*Populus tremula*, *Betula pendula*) with grass cover, *Tilia cordata*, predominated in Pre-Ural region, birch-aspen forest with nemorose species in the region of Kuznetsk Alatau undergrowth and cover of nemorose species. Plain, subtaiga.	-0.3	1.2	>3.3	0.9 to 3.3	0.9 to -1.5	-1.5 to -3.9	<-3.9
		Aspen-birch and birch-aspen forest with steppe grass cover. Plain, forest- steppe.	0.0	1.5	>4.5	1.5 to 4.5	1.5 to -1.5	-1.5 to -4.5	<-4.5
		Cedar and broad-leaved forest (*Quercus mongolica, Tilia taquetii, Pinus koraiensis*) with ferns and high grasses. Plain, broad-leaved forest.	0.5	1.1	>2.8	0.6 to 2.8	0.6 to -1.6	-1.6 to -3.8	<-3.8
		Spruce and fir-spruce forest, with low bush-moss and short grass cover. Plain, middle taiga.	0.6	1.3	>3.3	0.7 to 3.3	0.7 to -1.9	-1.9 to -4.5	<-4.5
		Broad-leaved and oak forest. Piedmont and mountain.	1.9	1.9	>7.3	3.8 to 7.3	0 to 3..8	0 to -3.8	< -3.8

Slightly warm boreal forest	Sensitive	Shrub-broad leaved forest sequence in river valleys.	4.5	3.5	>15.0	8.0 to 15.0	1.5 to 8.0	1.5 to -6.6	<-6.0
		Pine forest. Plain, outside boreal belt.	3.0	3.1	>12.3	6.1 to 12.3	-0.1 to 6.1	-0.1 to -6.3	<-6.3
		Dark coniferous with admixture of broad-leaved forest and broad-leaved and dark coniferous forest with undergrowth and cover of nemorose species. Plain, subtaiga.	2.9	2.3	>9.8	5.2 to 9.8	0.6 to 5.2	0.6 to -4.0	<-4.0
		Spruce-fir forest (*Abies nordmanniana, Picea orientalis*) frequently with *Fagus orientalis*. Plain, dark coniferous outside boreal belt.	3.3	2.7	>11.4	6.0 to 11.4	0.6 to 6.0	0.6 to -4.8	<-4.8
		Pine forest (*Pinus sylvestris*) with steppe grass cover undergrowth and cover of nemorose species. Plain, forest-steppe.	2.6	2.0	>8.6	4.6 to 8.6	0.6 to 4.6	-0.6 to -3.4	<-3.4
	Highly sensitive	Shrub-broad leaf-coniferous sequence in river valleys.	3.3	1.7	>8.4	5.0 to 8.4	1.6 to 5.0	1.6 to -1.8	<-1.8
		Lime-tree and oak forest. Plain, broad-leaved forest.	3.6	1.3	>6.2	3.9 to 6.2	2.3 to 3.9	2.3 to -0.3	<-0.3
		Pine-broad-leaf forest with boreal types in the cover. Plain, broad-leaf forest.	4.5	1.2	>8.1	5.7 to 8.1	3.3 to 5.7	3.3 to -0.9	<-0.9
Warm boreal forest	Sensitive	Beech forest. Piedmont and mountain forest.	7.2	2.4	>14.4	9.6 to 14.4	4.8 to 9.6	4.8 to 0	< 0.0
		Oak and hornbeam-oak forest Piedmont and mountain forest.	9.7	1.8	>15.1	11.5 to 15.1	7.9 to 11.5	7.9 to 4.3	<4.3
		Polydominant moist broad-leaved forest. Piedmont and mountain forest.	9.8	1.8	>15.2	11.6 to 15.2	8.0 to 11.6	8.0 to 4.3	<4.3