International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

Forest and Temperature Associations of Russia Relating to Global Climate Warming

Stolbovoi, V. and Nilsson, S.

IIASA Interim Report
October 1999

Stolbovoi, V. and Nilsson, S. (1999) Forest and Temperature Associations of Russia Relating to Global Climate Warming. IIASA Interim Report. IR-99-006 http://pure.iiasa.ac.at/5933/

International Institute for Applied Systems Analysis
Schlossplatz 1 • A-2361 Laxenburg • Austria
Telephone: (+43 2236) 807 342 • Fax: (+43 2236) 71313
E-mail: publications@iiasa.ac.at • Internet: www.iiasa.ac.at

Interim Report IR-99-006

Forest and Temperature Associations of Russia Relating to Global Climate Warming

Vladimir Stolbovoi (stolbov@iiasa.ac.at)
Sten Nilsson (nilsson@iiasa.ac.at)

Approved by

Gordon J. MacDonald (macdon@iiasa.ac.at)
Director, IIASA

22 October 1999

Contents

Abstract

We have developed forest and temperature associations for Russia that relate forest communities of Russia with mean annual temperature, standard deviation of mean annual temperature, and temperature tolerance limits. These associations are derived from analysis of the frequency of forest occurrence in different temperature regimes, and were interpreted in order to develop a framework for adaptation strategies for Global Climate Warming (GCW).

Acknowledgments

The authors thank Sylvia Prieler for computing the climatic data.

Forest and Temperature Associations of Russia Relating to Global Climate Warming

Vladimir Stolbovoi and Sten Nilsson

1. Introduction

The global climate warming (GCW) issue as recognized by scientists has now turned from a pure academic study to a policy issue. The Kyoto protocol is one example that policy-makers have started to formulate worldwide societal adaptation strategies (Berg, 1998). These strategies stipulate further scientific development in order to implement the policies. Despite the accumulation of climate-forest interaction knowledge by the forest science community within the few last decades, we are not yet in a position to give a comprehensive answer to many practical questions, for instance: What will the magnitude be of the GCW effect? How will the impact spread over time and space? What should be done in forest management to identify and adapt to GCW?

A great deal of the urgency answering these questions originates from the forest management cycle. A forest that is planted today is assumed to benefit the society during 80–100 years. That forest will not only generate wood supply, but also a wide range of environmental benefits. It is important for Russia in particular due to the tremendous extent of its forests and the strong dependence of local populations upon forest resources. In fact, Russia’s forest zone occupies more than 1130 million hectares (Mha), comprising about 66% of the country area[1] (Stolbovoi *et al.*, 1988). About 1090 Mha or 96% of this territory is classified by botanists as “northern” or boreal forests. As a vegetation community, the boreal forests have some specific peculiarities. They are characterized by low species diversity (mainly monodominant forest), simple stand structure, relatively low productivity

---

[1] The accuracy of area estimates in the study is within about 3%, due to the difficulty in determining the area covered by inner water bodies. At the 1:4M scale, water surfaces less than 400 km^2 (5x5 mm) are not identified. That is why the total country area on the digitized vegetation map used is about 1670 Mha. This figure is about 40 Mha less than the official country area of 1709.6 Mha.

(comparatively with tropical forest), and biomass stock of about 90 T/ha on average (Nilsson and Shvidenko, 1998).

Generally, the prediction of the effects of GCW on the vegetation is based on the climate-vegetational 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 nineteenth century when Gumbold first 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). In order to overcome data inconsistency between two phenomena, namely biosphere and atmosphere, the positioning of vegetation communities within climate parameters has been applied. The researchers have concentrated on recognizing direct climate characteristics, (solar radiation, temperature, precipitation, etc.) or indirect ones (humidity, aridity, continentality, evapotranspiration coefficients, etc.), which are highly correlated with the boundaries of the vegetation communities. This knowledge has been put to good use by climatologists (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 climate characteristics 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 the characteristics to establish climatic–vegetational units. The knowledge about the climate–vegetation associations has also been implemented in terrestrial models (i.e., Alcamo, 1994; Zinyowera *et al*., 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 and ignoring the real vegetation spatial distribution, it is presently the only concept that is implemented in the GCW studies.

From our point of view, this method fits many geographical tasks. However, it hardly meets requirements relevant to the GCW issue. In turn, this results in the present stagnation of both scientific and practical developments. For instance, numerous observations have documented that the local heterogeneity of vegetation responses on climate change is more divergent than comparing ecotone to climate variability (e.g., Graumlich *et al*., 1989; Luckman and Kavanagh, 1998). However, this fact, as will be demonstrated below, can not be incorporated in assessments of the GCW effects on terrestrial ecosystems within traditional approach, which makes urgently requested predictions very uncertain and thus unpractical.

The overall goal of this study is to investigate temperature-forest dependence[2] to identify temperature-forest associations that would be relevant for the GCW issue. We propose some easily accessible and widely available climate parameters be implemented as basic criteria and indicators for predicting forest behavior, and for developing adaptive strategies to counter the expected GCW.

2. Methods and Materials

The study was based on broad geographical information systems (GIS) analysis of vegetation and climate geo-referenced databases of Russia. This database was developed jointly through the efforts of numerous organizations under the leadership of IIASA, including FAO, the All-Russia Institute of Forest Resources and the Dokuchaev Soil Institute, Moscow, and others. The GIS tools were applied to investigate a dependence of the forest occurrence in Russia as a function of air temperature. To our knowledge, this is the first analysis of its kind for Russia and, probably the world.

Technically, we used a 5x5 km terrestrial grid with temperature (Leemans *et al*., 1991) and vegetation attributes (Stolbovoi *et al*., 1998) to define the frequency of forest occurrence and dependency of air temperature. This analysis allowed us to estimate the mean annual temperature that corresponds to the highest frequency of forest occurrence and, consequently, standard deviation of mean annual temperature and frequency of forest occurrence for each of the forest communities of the country.

---

[2] We simplify GCW as a complex integrated concept for temperature changes. The level of uncertainty increases when only a 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.

The forest communities descriptions were taken from the vegetation database (Stolbovoi *et al.*, 1998). At the scale of investigation (1:4M), the Russian territory comprises 48 forest vegetation communities. These communities are classified by dominant tree species, bioclimatic features (which are grouped into pre-tundra open woodland [forest-tundra], forest [mainly taiga[3]], forest-steppe zones and subzones), reliefs (plain and mountain), and antropogenic influences (primary and secondary forests).

According to the database, plain forest occurs on more than 650 Mha or 58% of the area. It is represented by the whole range of boreal bio-climatic forest zones. There are two common regularities in geographical patterns of forest distribution in Russia that influence trees species adaptability and survivability. The first is a zonality that deals with gradual changes of forest from north to south following an improvement of plant heat provision. The second is a faciality (provinciality) that reflects changes of climate continentally from west to east.

Mountain forests have an extent of 480 Mha, which corresponds to about 42% of the forests of the country. These regions have well-developed spectrums of vertical bio-climatic belts that incluence regular changes of the forest species depending upon two factors: (1) the temperature decrease with increased altitude and, (2) different heat conditions of slopes at various exposures. The bioclimatic differentiation due to exposure is well illustrated by the continental climate of East Siberia where high air pressure limits the local atmospheric circulation. The calm weather and the lack of horizontal exchange of air masses results in very contrasting temperature regimes depending on the rate of direct solar radiation, i.e., steppe vegetation might neighbor tundra. The vertical spectrum of forest belts generally looks like those of latitudinal vegetation zones moving northward.

3. Concept of Forest and Temperature Associations

Basic geography and ecology suggest that bio-climate regularities drive surface geosphere (weathering and geochemical processes) and biosphere (photosynthesis and biomass accumulation) development (Bailey, 1998; Budyko, 1974; Holdridge, 1967; Odum, 1971; Tansley, 1935). These environments have been permanently transformed attempting to approach thermodynamic equilibrium with atmosphere reaching a harmony with the geosphere, which often is regarded as a climax (Meeker and Merkel, 1984). In the "climate

---

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

envelope approach" (Henderson-Sellers, 1994), this concept can be illustrated by *Figure 1a*, where temperature-forest associations for the northern taiga of Russia are shown and assumed to be in equilibrium with the thermal conditions. As can be easily seen in *Figure 1a*, the temperature-forest interrelations are simple and forests are homogeneously distributed within their temperature niches. The application of this scheme to the GCW issue suggests the change of temperature limit will cause a shift of the forest communities consequently. The magnitude of the GCW effect on forest (as well as on other vegetation) has been adjusted through the account of changes in the area limited by certain temperature conditions. These limits are specified for the vegetation pattern, i.e., zone, community, etc. Following this assumption, the affected area could be calculated by the equation:

$$Yi = \frac{Si}{Ti}\Delta t \text{ , where}$$

Yi is the affected area of the forest community (*i*); *Si* is total area of forest community; *Ti* is the temperature interval (*Tmax-Tmin*) of forest community occurrence (temperature niche); and Δt is the temperature change caused by GCW.

The equation shows that the affected area (*Yi*) has linear dependence on temperature change (Δt). In the case that the latter is equal to the forest temperature niche (*Ti*), the forest can not survive and is expected to be completely replaced.

The problem with this approach is that it ignores the real heterogeneity of forest spatial distribution within a temperature niche. This assumption contradicts forest ecological fundamentals, limiting the implementation of the accumulated knowledge of forest diversity in densities and the succession dynamic in the GCW issue. In fact, forests, as any other biological object, manifests preferences to site conditions. The process of the site selection leads forests to form spatial heterogeneity in the form of concentrations in temperature niches favorable for specific tree species. This evidence coincides with major physiological processes occurring in a tree supporting photosynthesis, metabolism, transpiration, etc. Thus, a great diversity and dynamism of forest behavior can be associated with changes in temperature condition, i.e., the evidence that mature forest has either a lack of or an abnormally large amount of foreign undergrowth could be explained in many cases as the consequence of the temperature change. The latter case could accelerate the stocking increase in other sites within the same forest, etc. Clearly, the introduction of forest spatial heterogeneity in the GCW issue will significantly improve understanding of forest behavior and make estimates more reliable and practical.

In the range of different consequences of GCW on forests, which will be discussed briefly later, the replacement effect could be classified as the most dramatic. This process is discussed when talking about shifts of terrestrial ecosystems and relevant changes of climate related cycles (i.e., see Zinyowera *et al*., 1996). Therefore, a correct estimate of the vegetation replacement effect is the key task in the GCW issue. In the context of our paper, we suggest that forest segments will be subject to replacement if they appear outside their thermal ecological niche due to GCW. This situation will lead to the replacement of a given forest community by another more tolerant of a higher temperature condition forest association, or of non-forest vegetation.

The dependence of frequency of forest occurrence as a function of air temperature provides a rather comprehensive picture of various forest confusions caused by GCW (Stolbovoi, 1999). This concept uses more sophisticated data to adjust forest replacement segment as well as better describes a variety of forest temperature behaviors and responses as compared with those of the "climate envelope approach." *Figure 1b* shows the frequency of forest occurrence and dependence of temperature for northern taiga of the country. As can be seen, the distribution in consideration is considerably different from that one of *Figure 1a*. The shape of the curves has little in common with the square “climate envelope.” The curves obey normal Gaussian distributions, which can be observed for most randomly sampled characteristics of natural objects. In addition to the limits of using temperature niches (the envelopes presented in *Figure 1a*), the forests under consideration can also be characterized by mean annual temperatures and their standard deviation. These parameters seem to be very informative for a forest characterization related to GCW.

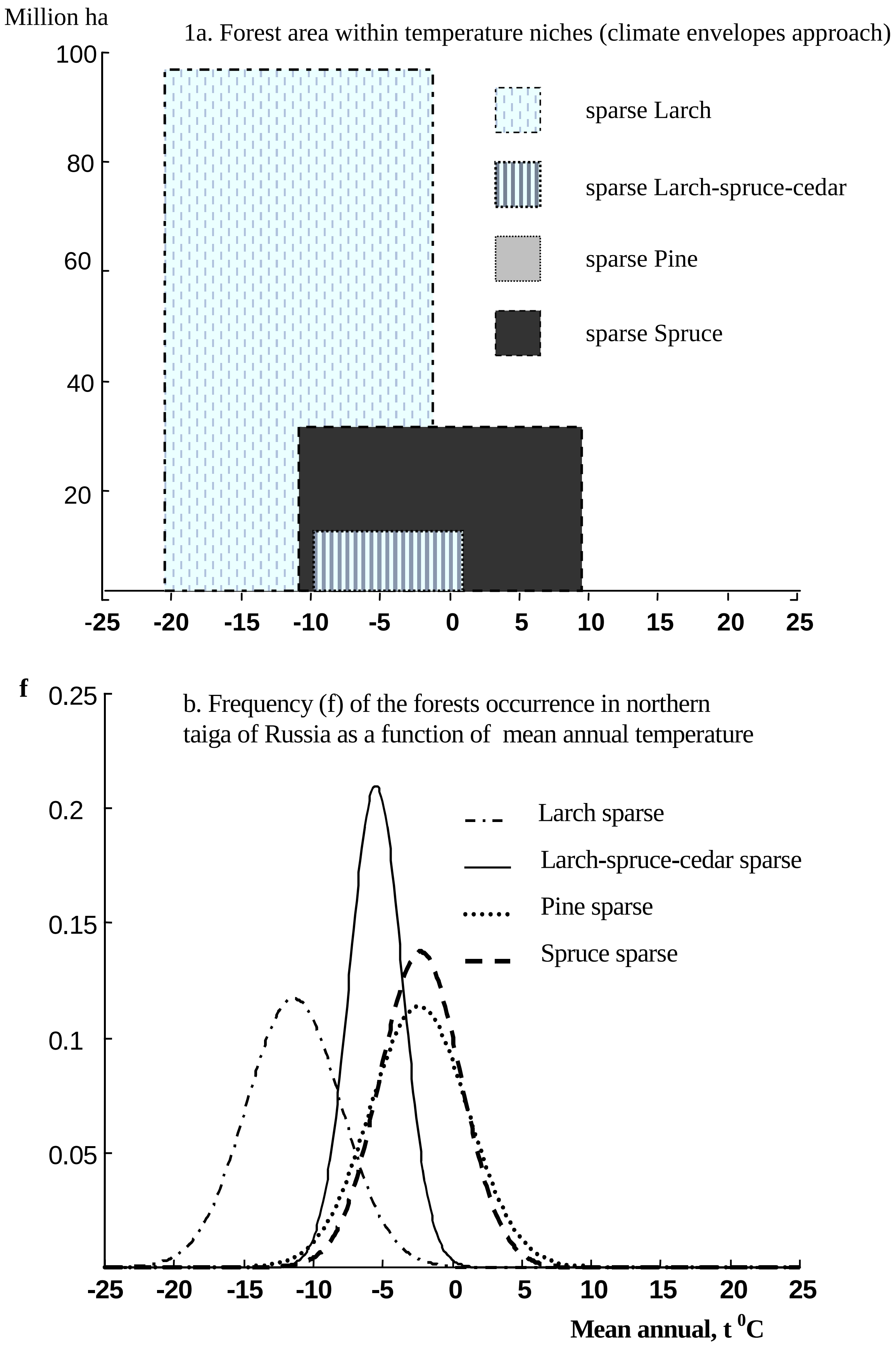
Mean annual temperature corresponds well to the highest frequency of forest occurrence. It identifies the temperature at which the forest population forms the highest density. The density consequently decreases when moving towards cooler and warmer temperature limits of the community occurrence. The information on the mean annual temperature also makes clearer understanding of thermal behavior and the interactions between various forest communities. For example, *Figure 1b* shows that sparse mixed 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 clearly identifies the compactness of the forest spatial distribution and could be used as a measurable indicator of forest sensitivity to GCW. For example, compare responses to the temperature change of the sparse larch-spruce-cedar forests for which standard deviation of the mean annual temperature is 1.9^0C with those of the sparse larch forests having a standard deviation of 4.2^0C.

The differences of forest-thermal behavior and, consequently, responses to temperature change depend upon the position of the segment of the forest community within temperature niche. This is well described (*Figure 2*) by mean annual temperature, which statistically identifies the cool or warm tolerance limits of forests. The GCW will cause heating stress and will lead to forest replacements where temperature increases exceed statistical upper tolerance limit. This effect could be identified by forest self-thinning. The cooler segment of the same forest community will benefit from the warming and probably perform the forest stocking increase. Some forest intervention might be expected on neighboring territories, which before the GCW had a temperature below the lowest statistical temperature threshold for the forest occurrence. This expansion is associated with the phenomenon of forest shifts northward (i.e., Kondrashova and Kobak, 1996; Zinyowera *et al*., 1996).

The factors mentioned above lead to the conclusion that forest responses to GCW, even within a single forest community, will be very diverse. This can be illustrated if we assume a temperature increase of around $+5^0$C and use *Figure 1b*. With this temperature change the sparse larch forests will be strongly effected by heating stress.

Figure 1: Temperature-forest associations of the northern taiga of Russia (Stolbovoi, 1999).



1a. Forest area within temperature niches (climate envelopes approach)

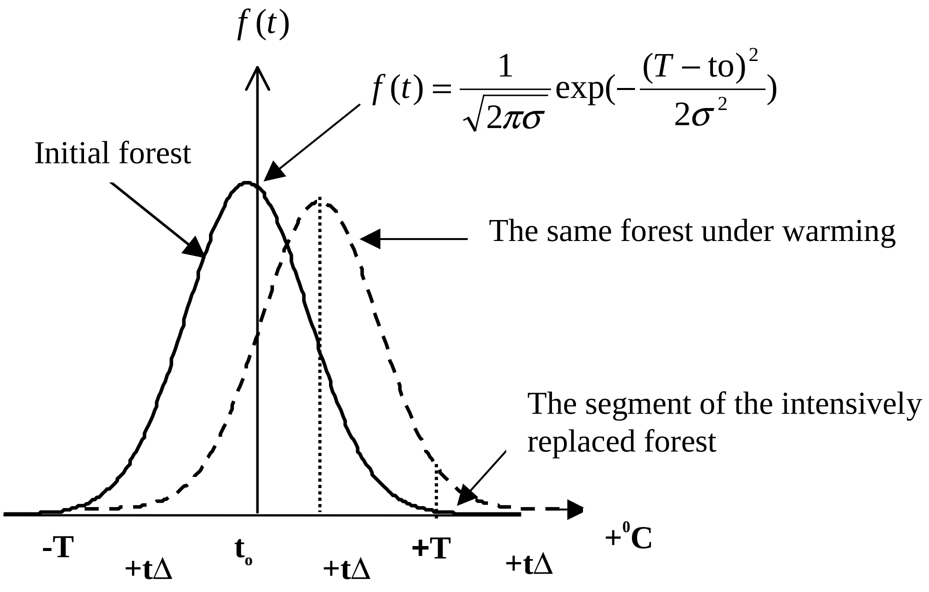
b. Frequency (f) of the forests occurrence in northern taiga of Russia as a function of mean annual temperature

Conversely, sparse spruce and pine forests will get improvement of their thermal behavior that might cause an increase of stocking. Lastly, sparse larch-spruce-cedar forest will probably be indifferent to this change.

As mentioned above, the frequency of forest occurrence and dependence of temperature follows Gaussian distribution, which is $N(t_0,\sigma)$ with a mean annual value of t_0 and with a standard deviation of $\sigma>0$ (*Figure 2*).

It seems realistic to identify a temperature range $[t_0-T,\ t_0+T]$ within which almost all forests occur. For instance, if $T\pm3\ \sigma$, 97% of the forest belong to this interval[4].

Figure 2: Forest in temperature shifts (Stolbovoi, 1999).



t_o – mean annual; +T – mean maximum; -T – mean minimum;

+tΔ – temperature increase

This makes it easy to establish different forest-response segments related to predicted GCW, i.e., to estimate the dynamics of the forest areas that will be replaced due to increased temperature. The task is trivial and has been well described by textbooks in

---

[4] The uncertainty of our GIS-based calculations is within 3%, which corresponds to this number in general.

mathematical statistics. The easiest way to introduce this approach is to assume gradual deduction of the forest area, which is caused by increased temperature.

If the temperature upper limit increases by $t\Delta$, then the forest segment that is indicated at the right side of the distribution curve (the segment of intensively replaced forest, *Figure 2*) could not survive because it will be out of the upper temperature tolerance limit. The deducted segment of the forest area can be estimated by the following standard equation:

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

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

where

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_0^{x \quad x=0} e^{-\frac{u^2}{2}} du,$$

The increase by the temperature at the range of 1σ might cause the replacement of about 1% of the forest community area.[5] Consequently, if the GCW happens to be at the level of 2σ, the area of the forest replacement will be around 17% of the total forest community, etc.

As suggested above, 97% of all forest communities exist inside the temperature niche $t_0 \pm 3\sigma$, which gives a temperature tolerance interval equal to 6σ. Applying the value of standard temperature deviation of mean annual temperature, it is easy to define segments of temperature-forest response classes (*Figure 3*). Based on σ value, it seems logical to distinguish forest occurring in the thermal conditions around mean annual temperature

---

[5] It should be noted that σ as a mathematical term has very limited general ecological or physiological significance. We use it in order to simplify our considerations. For practical use the ecologically sound temperature thresholds have to be introduced in the equation.

($t_0 \pm \sigma$) as segments of indifferent response to GCW. We assume that the latter forest segment is adapted to the yearly temperature variability and therefore, will not have any immediate responses to increased temperature. According to the Gaussian distribution, the indifferently responding segment occupies about 67% of the forests. These forests are expected to have normal development of forest successions.

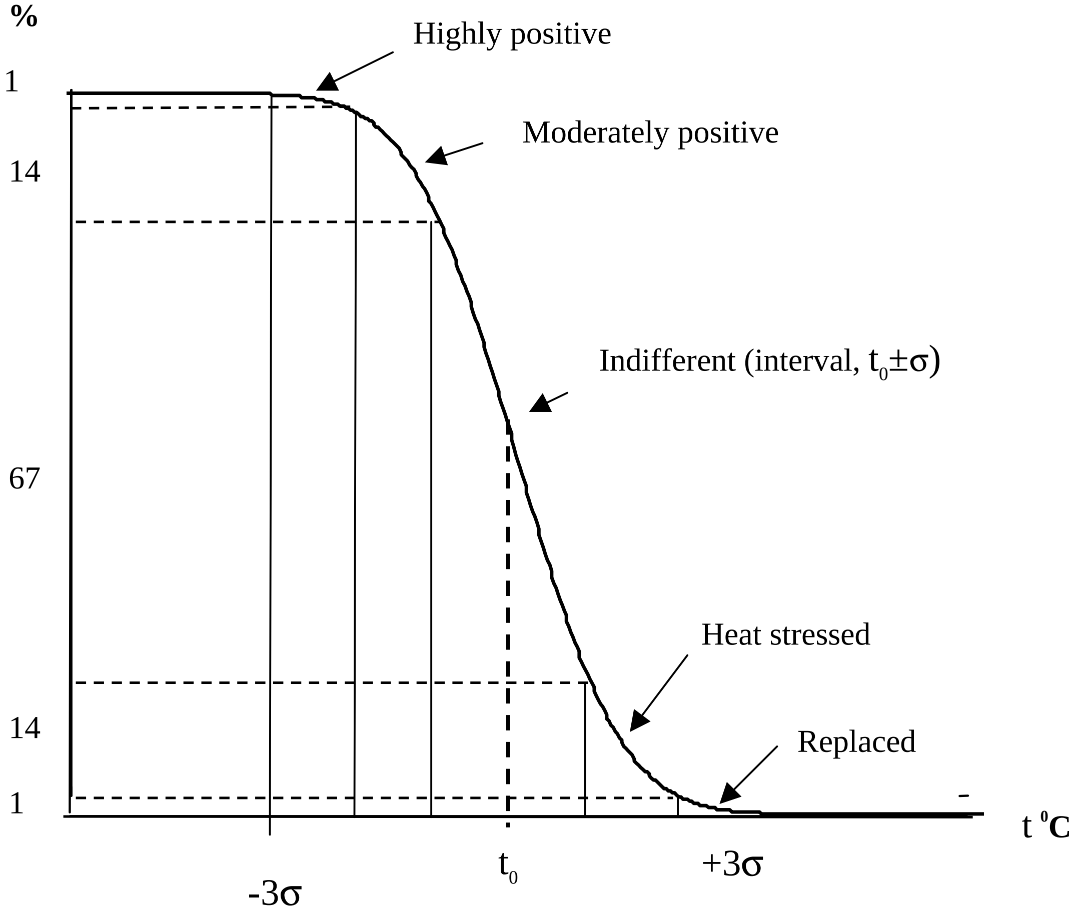
Forest segments (*Figure 3*) occurring within the interval from ($t_0 \pm 2\sigma$) to ($t_0 \pm \sigma$) will have different responses to GCW. A moderate increase of forest stocking could be expected by forests for which growing conditions will be improved by GCW. This will happen in the forest segments occurring in the conditions below mean annual temperature in the interval from ($t_0 - \sigma$) to ($t_0 - 2\sigma$). This forest segment can be identified by having increased stocking. It will be characterized by normal developments of the forest successions.

The strongest GCW effect can be expected on forest occurring within the temperature niche from ($t_0 - 2\sigma$) to ($t_0 - 3\sigma$) or at the lowest temperature threshold. Evidently, the massive increase of forest stocking has been observed in the northern taiga sparse larch forest at the polar Ural and explained by GCW influence (Viacheslav Kharuk personal communication).

A moderately self-thinning effect (*Figure 3*) of GCW is expected to occur in the sites where rising temperatures will cause increased heat stress. We expect this effect to be found in sites where the forest community's mean annual temperature falls within the interval from ($t_0 + \sigma$) to ($t_0 + 2\sigma$). A number of symptoms could identify this environment, i.e., the intervention of foreign successions that are not typical for the initial forest or the lack of adequate forest undergrowth in the over-mature forests, etc.

Forests occurring in the temperature interval from ($t_0 + 2\sigma$) to ($t_0 + 3\sigma$) are expected to have clear symptoms of replacement where temperature rise will exceed its upper thermo-tolerance limit. These forests will probably be subjected to massive intervention by neighboring forest communities that are better adapted to the warmer condition. Consequently, the appearance of abnormal forest successions will be observed.

Figure 3: Temperature-response segments (% of community) (Stolbovoi, 1999).



The conclusion can be drawn that the forest-temperature dependence that has been established and mathematically described allows us to introduce and account for a variety of forest responses formally. This approach makes it possible to incorporate recent research findings regarding a variety of forest responses to GCW (Graumlich *et al.*, 1989; Luckman and Kavanagh, 1998; Peterson, 1998, Stolbovoi, 1999).

Table 1 contains the essential temperature parameters required to estimate the responses across all forest of Russia.

4. Discussion

Historically, analyses of the impact of GCW on forests have dealt with very broad issues like location of forest zones, subzones, position of northern and southern boundaries, productivity change, etc. To our knowledge, research focusing on the behavior of forest community levels has not been carried out in Russia. This is due mainly to a lack of relevant information and tools. Our approach and IIASA's geo-referenced integrated database for the country allow such analysis to be made.

Table 1 illustrates that the broadscale analysis can be easily implemented providing rather sophisticated results on the expected magnitude of changes of the forest community position. Standard deviation of the mean annual temperature could be established as a definite measurable indicator of the sensitivity of the forest to GCW. For example, an increase of the temperature of 1σ might cause the replacement of about 1% of the total forest community area. It means for instance, a GCW of 4.2^0C for sparse larch forest (total area is 98.6 million ha) of the northern taiga will cause a replacement of 2 million ha of the forests. Consequently, if GCW happens to be at the level of 2δ (about 8^0C), the area with the sparse larch forest replacement will be about 16.8 million ha or around 17% of the total larch forest community. *Table 1* shows that various forests of Russia will have different responses to GCW. Probably, the most sensitive species are oak-hornbeam, hornbeam forests (*Carpinus betulus, Quercus robur*), *Acer pseudoplatanus, Cerasus aviumm* having a standard deviation of about 0.8^0C. The least sensitive community is sparse larch forest of the northern taiga subzone with a standard deviation of mean annual temperature of 4.2^0C.

An observation of standard deviation of the mean annual temperature values (*Table 1*) shows that only six forest communities from a total of 48 have σ around 1^0C. The majority of forests in Russia have a standard deviation of the mean annual temperature varying between 2-4 ^{0}C. The application of these values for the rough adjustment of the GCW effect on the extent of vegetation shifts definitely recognizes that in most of the studies the magnitude of the area change is considerably overestimated. For example, in the last broad assessment of the possible changes of the natural zone boundaries in the northern hemisphere (Kondrashova and Kobak, 1996), the conclusion has been drawn that the replacement area[6] for forest zones in Russia was expected to be 5.6% for broad-leaved forest, 13.7% for coniferous forest, and 19.7% for mixed forest. These estimates have been proposed for the annual temperature rise of 1.4 ^{0}C. The comparison of this result with the range of the standard deviations of the mean annual temperature for forest communities of Russia shows that this temperature increase might cause the replacement of less than 1% of the forest area. In order to meet the predicted effect, i.e., on coniferous forest (13.7% of replacements), the temperature would have to increase in the range of approximately 2δ or

---

[6] In the study, the replacement effect refers to % of the changes of the zones area.

roughly 5-8 ^{0}C, which is not realistic. Following the observation of the results of the major global circulation models, Ganopolsky reported (Ganopolsky, 1994) that the GCW effect could be expected to be in the 3-5 ^{0}C range at the end of the next century. Based on our analysis, even this warming might cause the replacement effect of 2-3% of the area that is occupied by coniferous forest. In our rough estimate we assume that about 97% of the coniferous forest in Russia is represented by larch and pine communities with the standard deviation of the mean annual temperature vary within 3-4 ^{0}C. The assumption could be made that for many places GCW will slightly exceed the value of standard deviation of the mean annual temperature (*Table 1*). It is necessary to note that in our consideration we do not take into account the GCW effect on the productivity change that will influence all terrestrial ecosystems totally.

The change in the location of the northern forest boundary[1] due to GCW is traditionally associated with the forest invasion of the tundra. Considering this problem, it is necessary to note that the transition between forest and tundra vegetation zones is very smooth, which leads botanists to designate the zone as ‘forest-tundra,’ an intermediate bioclimatic zone comprising something irregularly heterogeneous. In fact, some individual dwarf larch trees penetrate far into the tundra, or form separate groups that are surrounded by tundra. The lack of a precisely defined border leads to the situation where the boundary between tundra and forest is always a matter of convention (Körner, 1998). This leads us to the recognition that the assessment of the magnitude of forest intervention in tundra is also a problem of consensus. For example, should changes in vegetation caused by GCW be classified as forest invasion of tundra, (i.e., pioneer penetration of single trees into the neighboring tundra), northward forest expansion, or the increasing of forest stocking, etc?

In numerous studies, low temperature has often been regarded as the major constraint of forest expansion to the north. According to our data, this conclusion seems not to be correct if the mean minimum temperature is considered. We found that the temperature condition in the tundra is significantly warmer (due to the warming effect of the Arctic ocean) when compared with the conditions of the continental forest-tundra zone. For example, the 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. Therefore, spare larch forest might occur in the northern taiga at temperatures lower than those found in the pre-tundra zone (–36.0 ^{0}C vs. –34.2^{0}C [*Table 1*]). This fact leads to the conclusion that the low temperature does not directly control the position of the northern forest boundary. According to our data (*Table 1*) the scenario with temperature rises, i.e., of 1.4^0C (Kondrashova and Kobak, 1996), will not cause forest intervention in the tundra zone. From our point of view, the suggested expansion of forest vegetation on 60% of tundra area (Kondrashova and Kobak, 1996) seems to be rather confusing.

We do not project an intensive intervention of the forests to the northern tundra due to GCW. Looking inside forest zones and subzones (*Table 1*), one can find that the coolest locations have always been occupied by some specific forest community, which is mainly larch for the taiga, plain, and mountain forests. The difference between the coolest temperature limits for larch and other tree species is so large that it makes larch the most robust species for 96% of the boreal forests in Russia. For instance, the difference in temperature limits is about 17^0C between sparse larch and its closest ecological neighbor, sparse spruce forest in the pre-tundra zone. The difference is 8^0C for larch and cedar-spruce-fir forest in the southern taiga subzone. This evidence leads us to believe that the most visible changes in the forest-tundra zone could be associated with an increase of the stocking of larch sparse forests. However, this evidence could be also classified as forest invasion of the tundra.

The southern forest boundary is assumed, due to climate warming, to be shifted to the north. The expectation is that the steppe vegetation will expand northward at the cost of forested area. Based on the principal scheme (*Figure 2*), it seems that the probability of this development is rather high. Undoubtedly, GCW will influence the forest occurring under conditions close to its upper temperature limit. It seems that, in the long-term, existing tree species positioned out of their temperature niche will not able to avoid heat stress even if the amount of precipitation is sufficient to allow adaptation mechanisms (Levitt, 1980). Some arguments for this statement are given below.

The upper mean maximum temperature (*Table 1*) for the plain boreal forest of Russia is 19.4^0C. This value has been recorded for pine forest (*Pinus sylvestris*) in the forest-steppe bioclimatic zone. It is important to note that the mean maximum temperature limit of forest occurrence in the country is about 20.8^0C, which is observed for temperate broad-leaved forest. These two figures are very close (the difference is only 1.4^0C), which allows us to conclude that both forest types will be affected equally by GCW. From our point of view, the common temperature characteristics of Russian boreal forest indicate its high elasticity to cold and low resistance to heat. This statement does not contradict the common opinion that the northern forest will be more adversely affected by GCW than the southern. As we mentioned, we associate the changes in the north with the intensive increase of forest stocking, while the replacement of forest by non-forest vegetation probably could be observed on the southern forest boundary. This finding challenges the view of forest responses by focusing attention on it diversity and complexity, ranging from slight changes in behavior and productivity to the replacement affect.

Mixed forest communities in the boreal zone have always had instabilities that coincide with the lower values of the standard deviation of the mean annual temperature (Stolbovoi, 1999). This lower value varies around 1–2^0C, which is considerably less than those for the monodominant forest where this value is always more than 3–4^0C. Mixed forest occupies very limited areas within all forest zones and subzones in Russia (*Table 1*). This fact illustrates that the extent of the increase of mixed forest can not be predicted. We can predict only that mixed forest will increase as the transition occurs.

The present paper is devoted to the temperature-vegetation effects initiated by GCW. On the other hand it is well-known that other than temperature climate characteristics, i.e., continentality, air humidity, wind regime, etc., have to be heavily introduced in order to make the prediction of these effects reliable. In this context, some remarks should be made on behavior of mixed forest as it depend on climate humidity.

Mixed forest is rather typical for southern taiga and this can be associated with climatological cycling of precipitation. According to Rode (1978), every climate is subjected to 11-, 45-, and 90-year hydrological cycles. This fluctuation plays a particularly important role for forests occurring in regions with a humidity coefficient close to 1.0 (precipitation is equal to the evaporation). The humidity coefficient for the southern taiga (Soil Geographical Regionalization of the USSR, 1962) subzone ranges from 1.3 to 0.7. It is obvious that monodominant forests have no adaptation mechanism to the recurrent climate. These forests can not successfully survive in a series of the dry years if they prefer wet growing conditions and, conversely, will suffer from a long period of wet years if they are suited to grow in dry environments. In this variable climate, the mixed forests have a highly resilient capacity and are the best adapted to different climates. The pluvial phases give favor to the development of the hydrophilic tree species while the arid phases advance the behavior of the hydrophobic tree species. This argument leads to the conclusion that other than the GCW factor, namely precipitation patterns will play a key role in the possible expansion of the mixed forest in the southern taiga subzone.

Similar conclusion can be made regarding probable expansion of the spruce and fir forests, which also require specific changes in environment, i.e., increasing air humidity, decreasing wind activity, increasing snow depth, etc. This means that the number of climate parameters implemented in the global circulation models has to be significantly extended in order to study the impacts on forests. As reported by numerous studies (i.e., Ganapolsky, 1994), the problem with introducing climate characteristics other than temperature is that the reliability of the forecasts is then very low. This makes it impossible to implement these characteristics in climate change predictions. In turn, the assumptions based on limited number of parameters for some forest communities are still rather provisional.

5. Conclusions

1. New temperature-forest associations have been developed for Russia. They have been derived from an investigation of the frequency of forest occurrence as a function of temperature. In addition to the traditional temperature tolerance limits for forest zones and subzones, this approach generates a set of temperature characteristics essential for making more reliable assessments of GCW effects on the total forest communities across the country.
2. The frequency of forest occurrence over temperature obeys a Gaussian distribution pattern and thus, can be properly described by mean annual temperature and its standard deviation. We propose that these characteristics be applied for determining the magnitude of the impact of GCW and its dynamics depending upon a gradual temperature increase. These parameters allow us to identify parts of the forest community with different temperature change responses.
3. In addition to the established view that GCW will strongly affect the northern forest zones and the position of the northern forest border, the attention has been drawn to the southern forest boundary that will probably be the area of the most dramatic forest conversions resulting in replacement of forests by non-forest vegetation.
4. A massive intervention of larch forest to the north due to GCW is not expected. We assume that the most dramatic changes will likely be associated with the transformation of the composition of forest communities within zones and subzones (with some increase of the share of the mixed forests in transitional period) and the improvement of

the larch forest performance in all vegetation zones. To predict development of spruce and fir forests, as well as broad-leaved forests, some additional climate parameters, i.e., precipitation, air humidity, wind regime, snow cover, etc., have to be analyzed. In fact, the scenarios for these factors in GCW studies are very uncertain, which makes the suggestions on their responses rather provisional.

6. References

Alcamo, J. (ed.), 1994. *IMAGE 2.0. Integrated Modeling of Global Climate Change.* Dordrecht, The Netherlands: Kluwer Academic Press, 318.

Alisov, B.P., 1956. Climate of the USSR. Moscow: Moscow State University publ., pp. 128 [in Russian].

Archibold, O.W., 1995. Ecology of World Vegetation. London: Chapman & Hall, pp. 510.

Bailey, R.G., 1996. Ecosystem Geography. New York: Springer-Verlag, pp. 204.

Bailey, R.G., 1998. Ecoregions. The Ecosystem Geography of the Oceans and Continents. New York: Springer-Verlag, pp. 178.

Bazilevich, N.I., 1993. Geographical Productivity of Soil-vegetational Formations in Northern Eurasia, *Soil Science (Pochvovedenie)*, **10**:10–18 [in Russian].

Berg, M., 1998. The Kyoto Protocol – Next Step on a Long, Bumpy Road. *Climate Change*, **40**: 4-7, NRP Office Publication.

Budyko, M.I., 1974. Climate and Life (English edition by D.H. Miller). New York: Academic Press, 508.

Dokuchaev, V.V., 1951. To Study: Natural Zones. Selected publications, Vol. 4, Academy Press, Moscow-Leningrad, [in Russian].

Ganopolsky, A.V., 1994. Climate Change Scenarios for Boreal Forest Zone. Working document (unpublished manuscript). Laxenburg, Austria: International Institute for Applied Systems Analysis, 59 p.

Graumlich, L., Brubaker, L.B., Grier, C.C., 1989. Long-term Growth Trends in Forest Net Primary Productivity. Cascade Mountains, Washington. *Ecology*, **70**, pp. 405–410.

Grigoriev, A.A. and Budyko, M.I., 1956. On a Periodic Law of Geographical Zonality. Reports of the Academy of Science, **110**, No. 1, Moscow, pp. 129–132.

Henderson-Sellers, A., 1994. Global Terrestrial Vegetation “Prediction”: The Use and Abuse of Climate and Application Models. Progress in Physical Geography **18**:2, Edward Arnold, pp. 209–247.

Holdridge, L.R., 1967. Life Zone Ecology. Tropical Science Center, San Jose, Calif., USA.

Hunt, C.V., 1974. Natural Regions of the United States and Canada. San Francisco, W.H. Freeman, pp. 723.

Kondashova, N.Yu. and Kobak, K.I., 1996. Possible Global Warming Caused Changes of the Natural Zones Boundaries in the Northern Hemisphere. Problems of ecological monitoring and ecosystem modeling. Vol. XVI, St. Petersburg, Gidrometeoizdat, 90-99 p.

Köppen, W., 1936. Das geographische System der Klimat. In: Handbuch der Klimatologie, Köppen, W. and Geiger, R. (eds.). Berlin: Gebrüder Bornträger.

Körner, C., 1998. Worldwide Positions of Alpine Treelines and Their Causes. Beniston, M. and Innes, J.L. (eds.). Lecture Notes in Earth Sciences, **74**, The Impacts of Climate Variability on Forests, Springer-Verlag, Berlin, Heidelberg, pp. 221–229.

Leemans, R. and Cramer, W., 1991. The IIASA Climate Database for Mean Monthly Values of Temperature, Precipitation, and Cloudiness on Terrestrial Grid. RR-91-18, IIASA, Laxenburg, Austria, pp. 62.

Levitt, J., 1980. Responses of Plants to Environmental Stresses. Vol. II. Water, Radiation, Salt, and Other Stresses. Academic Press, Inc., pp. 607.

Luckman, B.H. and Kavanagh, T.A., 1998. Documenting the Effects of Recent Climate Change at Treeline in the Canadian Rockies. Beniston, M. and Innes, J.L. (eds.). Lecture Notes in Earth Sciences, **74**, The Impacts of Climate Variability on Forests, Springer-Verlag, Berlin, Heidelberg, pp. 121–144.

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

Nilsson, S. and Shvidenko, A., 1998. Is Sustainable Development of the Russia Forest Sector Possible? IUFRO Occasional Paper No. 11, ISSN 1024-414X, Vienna, 77p.

Odum, E.P., 1971. Fundamentals of Ecology. Third edition, W.B. Saunders Company, Philadelphia, London, Toronto, pp. 574.

Olson, J.S. and Watts, J.S., 1982. Major World Ecosystem Complexes. In: Carbon in Live Vegetation of Major World Ecosystems. ORNL-5862. Oak Ridge, TN: Oak Ridge National Laboratory. 1:30 000 000.

Peterson, D.L., 1998. Climate, Limiting Factors and Environmental Change in High-altitude Forest of Western North America. Beniston, M. and Innes, J.L. (eds.). Lecture Notes in Earth Sciences, **74**, The Impacts of Climate Variability on Forests, Springer-Verlag, Berlin, Heidelberg, pp. 191–208.

Prentice, I.C., Cramer, W.P., Harrison, S.P., Leemans, R., Monserad, R.A. and Solomon, A.M., 1992. A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate. *Journal of Biogeography*, **19**, pp. 117–134.

Prentice, I.C., Sykes, M.T. and Cramer, W., 1993. A Simulation Model for the Transient Effect of Climate Change on Forest Landscape. *Ecol. Modelling*, **65**, pp. 51–70.

Rode, A.A., 1978. The Problems of the Soil Water Regime. *Gydrometizdat*, Leningrad, pp. 212 [in Russian].

Soil-geographical Regionalization of the USSR, 1962. Academy Press, Moscow, pp. 422, [in Russian].

Stolbovoi, V., Fischer, G., Ovechkin, V.S. and Rozhkova (Kravets), S., 1998. The IIASA-LUC Project Georeferenced Database of the Former USSR, Vol. 4: Vegetation, IR-98-114, IIASA, Laxenburg, Austria.

Stolbovoi, V., 1999. Classification of Russia's Forest in Relation to Global Climate Warming. IR-99-005, IIASA, Laxenburg, Austria, 24 p.

Tansley, A.G., 1935. The Use and Abuse of Vegetational Concepts and Terms. Ecology 16, pp. 284–307.

Thornthwaite, C.W., 1948. An Approach Toward a Rational Classification of Climate. Geographical Reviews, **38**, pp. 55–94.

Woodward, F.I., 1987. Climate and Plant Distribution. Cambridge University Press, Cambridge, pp. 174.

Zinyowera, M.C., Watson, R., Moss, R. and Dokken, D., (eds.), Climate Change 1995, 1996. Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assesssment Report of the International Panel on Climate Change. Cambridge University Press, 97–122.

Table 1: Forest-temperature associations of Russian forest biome

FOREST COMMUNITY	**EXTENT**		**TEMPERATURE, ^{0}C**		
	Million ha	% of zone/of biome	Tmin/Tmax	Tmean annual	δ
DARK AND LIGHT CONIFEROUS, BROAD-LEAVED FORESTS, OPEN WOODLANDS					
Plain forests					
Boreal forests and open woodlands					
Pre-tundra open woodlands					
Larch forest with low bush-lichen-spruce cover	25.5	80	-34.2/12.4	-12.2	3.3
Spruce forest (*Picea obovata*) with mosaic low shrub-spruce cover	4.7	15	-17.7/12.6	-3.6	1.1
Birch forest (*Betula czerepanovii* with *Pinus sylvestris, Picea obovata*) with short grass-low bush and spruce cover	1.7	5	-11.8/11.4	-1.5	0.9
Total	31.9	100/3	-34.2/12.6		
Northern Taiga					
Larch sparse forest with low bush-moss and low bush-lichen cover	98.6	60	-36.0/14.2	-11.4	4.2
Spruce sparse forest with *Betula nana* in low bush-lichen-grass undergrowth	28.3	17	-17.5/14.2	-2.3	2.9
Pine sparse forest with low bush-grass-lichen cover	28.1	17	-17.7/15.1	-2.4	3.5
Larch-spruce-cedar sparse forest (*Pinus sibirica, Picea obovata, Larix sibirica*) with low bush-lichen cover	9.5	6	-24.8/15.7	-5.5	1.9
Total	164.5	100/14	-36.0/15.7		
Middle Taiga					
Larch forest	97.3	48	-34.8/16.5	-8.4	3.1
Pine forest with low bush-moss and lichen cover	48.0	24	-20.8/16.6	-2.2	4.4
Spruce and fir-spruce forest with low bush-moss and short grass cover	35.9	18	-14.1/16.2	0.6	1.3
Spruce-cedar and cedar-spruce forest (*Pinus sibirica, Picea obovata*) with grass-low bush-moss cover	20.7	1.0	-22.4/16.7	-3.2	1.5
Total	201.9	100/18	-34.8/16.7		

FOREST COMMUNITY	EXTENT		TEMPERATURE, ^{0}C		
	Million ha	% of zone/of biome	Tmin/Tmax	Tmean annual	δ
Southern Taiga					
Spruce, fir-spruce and spruce-fir forest with mosaic grass-low bush and grass-moss cover	54.0	45	-14.5/17.3	1.3	2.4
Pine (*Pinus sylvestris*) and larch-pine forest with grass-moss (*Pinetum hylocomiosum*) and low bush-lichen-moss cover	32.9	28	-18.4/17.4	-0.5	4.4
Cedar-spruce-fir forest (*Abies sibirica, Picea obovata, Pinus sibirica*) with mosaic short grass-moss cover	19.8	17	-21.5/17.3	-2.0	1.3
Larch (*Larix gmelinii*) and pine-larch forest with low bush-grass cover	12.6	11	-29.5/18.4	-4.0	1.6
Total	119.3	100/11	-29.5/18.4		
Sub-taiga					
Dark coniferous with a mixture of broad-leaved forest and broad-leaved and dark coniferous forest with undergrowth and cover of nemorose species	31.7	43	-11.8/17.7	2.9	2.3
Pine forest (*Pinus sylvestris*) with grass cover, forest frequently with pine and meadow-steppe species (southern border)	27.0	36	-18.4/17.8	-0.2	3.3
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	12.7	17	-19.2/17.7	-0.3	1.2
Larch forest (*Larix gmelinii*) with *Quercut mongolica, Betula davurica* and other grass species	2.6	4	-27.2/19.6	-1.8	1.9
Total	73.9	100/7	-27.2/19.6		

FOREST COMMUNITY	**EXTENT**		**TEMPERATURE, ^{0}C**		
	Million ha	% of zone/of biome	Tmin/Tmax	Tmean annual	δ
Steppe-forest					
Pine forest (*Pinus sylvestris*) with steppe grass cover	5.1	55	-14.8/19.4	2.6	2.0
Aspen-birch and birch-aspen forest with steppe grass cover	4.3	45	-19.1/18.2	0.0	1.5
Total	9.4	100/1	-19.1/19.4		
Mountain Forest					
Boreal forest and open woodlands					
Sub-goltsy (tundra belt above the forest line) open woodland					
Larch forest with low bush-moss-lichen cover	94.7	58	-35.9/12.7	-12.2	3.5
Pine forest (*Pinus pumila)* with larch open woodland and tundra	64.4	40	-27.9/12.0	-9.0	5.0
Dark coniferous forest with low bush-moss-lichen cover	3.5	2	-27.0/14.2	-6.3	3.2
Total	162.5	100/14	-35.9/14.2		
Mountain taiga forest					
Larch forest	184.9	62	-32.1/14.9	-8.2	4.1
Cedar-spruce and fir-spruce forest	23.1	8	-24.0/14.5	-4.2	3.4
Spruce-fir and cedar-fir forest with grass-low bush cover	21.9	7	-20.5/15.9	-2.5	2.1
Cedar and fir-cedar forest (*Pinus sibirica, Abies sibirica, Larix sibirica, Picea obovata*) with low bush-short grass-spruce cover	21.8	7	-23.8/14.2	-4.6	2.3
Spruce-fir, cedar-fir, fir-spruce forest with nemorose elements	18.6	6	-19.4/16.2	-0.7	2.4
Pine forest (*Pinus sylvestris*)	17.7	6	-21.2/16.5	-2.0	2.7
Birch forest (*Betula lanata*) with high grass cover	9.4	3	-16.3/11.7	-2.6	2.1
Total	297.3	100/26	-32.1/16.5		

FOREST COMMUNITY	**EXTENT**		**TEMPERATURE, ^{0}C**		
	Million ha	% of zone/of biome	Tmin/Tmax	Tmean annual	δ
Dark coniferous forest outside boreal belt					
Spruce-fir forest (*Abies nordmanniana, Picea orientalis*) frequently with *Fagus orientalis*	0.3	70	-6.5/12.7	3.3	2.7
Pine forest	0.1	30	-7.3/12.6	3.0	3.1
Total	0.5	100/<1	-7.3/12.7		
BROAD-LEAVED					
Plain forest					
Lime-tree and oak forest	22.4	71	-11.7/18.8	3.6	1.3
Oak forest	5.9	19	-24.3/20.2	-0.1	2.5
Pine-broad-leaved forest with boreal types in the cover	1.6	5	-10.1/18.8	4.5	1.2
Cedar and broad-leaved forest (*Quercus mongolica, Tilia taquetii, Pinus koraiensis*) with ferns and high grasses	1.0	3	-23.3/20.3	0.5	1.1
Oak-hornbeam, hornbeam forest (*Carpinus betulus, Quercus robur*) with *Acer pseudoplatanus, Cerasus aviumm*	0.6	2	-26.8/20.8	-2.0	0.8
Total	31.5	100/3	-26.8/20.8		
Piedmont and mountain forest					
Cedar-broad leaved forest (*Quercus mongolica, Betula costata, Pinus koraiensis*) high grassy	7.5	44	-22.3/18.6	0.0	2.1
Broad-leaved and oak forest	5.2	30	-16.2/17.9	1.9	1.9
Oak and hornbeam-oak forest	3.2	18	-1.7/20.9	9.7	1.8
Beech forest	1.1	6	-4.2/18.2	7.2	2.4
Polydominant moist broad-leaved forest	0.3	1	0.2/19.2	9.8	1.8
Total	17.1	100/2	-16.2/20.9		

FOREST COMMUNITY	**EXTENT**		**TEMPERATURE, ^{0}C**		
	Million ha	% of zone/of biome	Tmin/Tmax	Tmean annual	δ
ECO-DYNAMIC SEQUENCES OF ALLUVIAL COMMUNITIES, SECONDARY (ANTROPOGENIC) MEADOWS AND AGRICULTURAL LAND					
Shrub-coniferous sequence	8.9	34	-27.7/16.4	-5.7	5.8
Shrub-broad leaved forest sequence	7.6	29	-12.3/20.6	4.5	3.5
Shrub-small leaved forest sequence (*Betula pendula, Populus tremula, P.nigra, P.alba*)	2.4	9	-20.1/17.8	-0.8	0.9
Shrub-small leaved forests and steppe meadows sequence	1.0	4	-22.8/17.0	-2.0	3.3
Shrub-broad leaved-coniferous sequence	0.3	1	-10.8/18.0	3.3	1.7
Total	20.2	100/2	-27.7/20.6		
Total forest biome	1130.1		-36.0/20.9		