Forest Zones of Siberia as Determined by Climatic Zones and Their Possible Transformation Trends under Global Change

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A system of zoning in Siberia has been formed under the control of continentality, which provides the heat and humidity regimes of the forest provinces. Three sectors of continentality and four to six boreal subzones form a framework for the systematization of the different features of land cover in Siberia. Their climatic ordination provides the fundamental basis for the principal potential forest types (composition, productivity) forecasting the current climate. These are useful in predicting the future transformations and successions under global changes.

Keywords: Siberia, climatic ordinations, zonal forest types, modelling

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1 Introduction

The global change in climate and its impact on the vegetation, primarily on the forests, is discussed at different levels – from the global to the regional. The priority of climatic factors – warmth and water supply – is illustrated at the global level by advanced global biome models (Pretice et al. 1992, Solomon and Cramer 1993, Cramer and Solomon 1993, Tchebakova et al. 1992, 1994).

With the purpose of anticipating the effects of potential global warming, we applied experimental data on the climate-soil-vegetation links in different landscape zones and provinces of Siberia.

It is known that these links are not global but regional. Nevertheless, the first attempts to predict modern forest zones and subzones of Siberia on the basis of climatic indices were successful. All the models created have proved remarkably adequate in reproducing broad subcontinental-scaled patterns of biomes and zones (Pren-
The authors note that their approaches differ from that of Holdridge and Box and that they have some advantages for future biome modelling. All the models are static (equilibrium) and there are some limitations when they are applied to study land cover and forest ecosystems.

The purpose of this paper is (i) to present the forest zones and formations of Siberia on climatic ordination schemes and (ii) to discuss the ways these graphic portraits could be made use of in modelling. Formations and zones are traditional for Russian scientific literature (Vegetation 1990).

3 Results and Discussion

A great number of altitudinal subzones were classified as follows (Fig. 1): subgolets-taiga woodland ecotone (1), subalpine dark-foliaged taiga (2), mountain taiga (3) dominated by fir (Abies sibirica) under a superhumid climate, by pine (Pinus sibirica) under a humid climate and perhumid climate, and by larch (Larix sibirica) mostly under a semi-humid climate. Mixed light-foliaged taiga with birch, or subtaiga (4) are zonal in low hills under a moderate humid climate. Three variants differ in composition, structure and productivity. Some of them are very similar to forest-steppe. The most humid subtaiga variant consists of aspen. Dark-foliaged "chern" taiga (5), mostly of fir, covers the windward macroslopes under perhumid climate. The forest-steppe ecotone (6) is typical under semi-humid and cool climates and winddrilled under cold climates. Mountain steppe and tundra also take their position and replace the boreal forest according to factors of humidity and heat supply, which limit the spread of the boreal forest. Sectors A, B, C, D appear as sectors of humidity, with their specific bioclimatic variants of mountain forests and soils. These belt spectra of forests have been described in the literature (Smagin et al. 1980, Polikarpov et al. 1986). We refer to them as the superhumid fir zone, humid dark-foliaged, semi-humid larch, and semi-arid larch-steppe.

This subdivision is not entirely the same as the life zone classification (Holdridge 1967), but it is close to it. Our subdivision is based on empirical data. The values of the boundary between the forest and the steppe are minimal in Yakutia, where permafrost is the factor favourable for the growth of larch forests (Budyko 1971, Bueks 1977). Sector A shows only one situation, rather typical for zonal and mountain vegetation in the most continental (ultra-continental) part on eastern Eurasia. The steppe of Mongolia rise up to the mountain tundra, into close contact with mountain taiga. Superhumid (rain) forest is represented only on the windward slopes in several regions of southern Siberia, but it is fairly specific and not typical for Siberia as a whole. One can see some features of similarity with the dark-foliaged forest ecosystems of the Far East.

In 1987–1994, the authors of different versions of bio-climatic ordinations for Siberian zones used the same approach. They allow one to conclude that the climatic regimes of the zones (as well as the altitudinal belt complexes) express a certain degree of warmth and relative humidity, and the climatic indices are the main system-forming factors of zonality. They determine the most typical features of the structure and composition of the forest cover and landscape as a whole: the seasonal rhythms of natural processes, potential productivity, some soil processes. The climate-vegetation links were formed during the last part of the Holocene when forest zones emerged first of all as a result of biotic adaptation to the continental boreal climate and to soil conditions.

We were often assured that the supply of warmth and water, together with the regional biotic composition, were the major inputs in bio-climatic systems called "zones", subzones, and their variants. The sectors of continentality and zones, which are multi-dimensional within the climatic context, but two-dimensional in the advanced graphic portraits, form the matrix system, summarising all information on forests, their structure, stability, and successions. This cannot be regarded as an underestimate of soil factors.

The composition and diversity of regional biota and vegetation pattern are of great importance for predictive modelling. Hence, regional bioclimatic models are preferable for many purposes of mountain and plain forestry in Siberia. It should be noted that the range of tree species in the

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**Fig. 1.** The first conceptual model of the oroboreal forest. Altitudinal zones, biomes, and forest formations of South Siberian mountains in the climatic context: annual precipitation (Pmm) and active temperature sum (T > 10) (Polikarpov & Nazimova 1976). 1 – Subgolets taiga (dark-foliaged) and larch woodlands; 2 – Subalpine woodlands (dark-foliaged); 3 – Mountain taiga (larch, dark-foliaged, mixed); 4 – Subtaiga (light-foliaged and mixed birch light-foliaged); 5 – Chern taiga (dark-foliaged) and "chern" mixed forest; 6 – Forest-steppe (larch and mixed pine-birch); 7 – Mixed species; 8 – Semi-arid larch-steppe, semi-humid larch, humid, and perhumid dark-foliaged, super-humid fir.
mountains of southern Siberia, as well as in Siberia as a whole, is narrow. This makes the models less informative as regards composition and productivity in both zonal and inter-zonal formations and forest types.

In addition to Fig. 1, presenting the climax formations and quasi-climax pyrogenic (postfire) formations, we have developed versions demonstrating the derivative anthropogenic stands, as well as zonal series and major forest types (Poliakov et al. 1986).

Fig. 2 demonstrates the majority of plain and tableland Siberian zones in two-dimensional climatic context of the supply of warmth and humidity. Three zonobiomes - steppe, taiga, and tundra – take their places within the climatic context of Active Temperature Sums and Dryness Index. All meteorological stations representing dark-foliaged zonal forest types took their places only within the small, more humid part of the climatic context with DI equalling 0.5–0.8.

**Pinus sibirica**, *Picea obovata*, and *Abies sibirica* within the southern subzone form mixed stands of dark-foliaged forest types. Birch and pine, and sometimes aspen, are common following forest fires and clear-felling of forest. They are not shown as secondary forests in Fig. 2, but these tree species should studied as potential constituents of future forests as they are more resistant to high levels of radiation, to drought, and other stresses.

**Pinus sylvestris** dominates light-foliaged southern taiga and forms quasi-climax forest types in central Siberia. Larch taiga on permafrost occupies the remainder of the climatic context. Geographically, this is northern and eastern Siberia. Pine and birch sub-taiga with an admixture of aspen occurs under warm but sufficiently moist climates (GDD 1400–1700 and DI 2.0–3.0) while the forest-steppe forms the transition zone from sub-taiga to steppe under a semi-humid climate (DI 1.0–1.8).

Generally speaking, the distribution of zonal formations has confirmed the principal scheme of zonality in Siberia developed by Siberian botanists (Shumilova 1962). Besides, it should be mentioned that in the 1970s Finnish botanists emphasised zonal features within the boreal zone of Eurasia. They demonstrated the great potential of comparative analysis of vegetation zones abundant all over their range (Hämet-Ahti 1974, 1980, and others). According to field investigations, Hämet-Ahti suggested four subzones within the boreal zone (northern, middle, southern boreal, and hemiboreal) – these differing distinctly not only in terms of their flora but also in terms of their productivity, agricultural potential, seasonality, and other functional phenomena. This approach is rather close to the approach taken by Russian geobotanists. Besides this, the authors supported the concept of sectoral or longitudinal subdivision, as well as predicting the boreal (or boreoreal) steppe lands within the continental sectors of Eurasia (Yakutia, Northern Mongolia, Trans-Baikal region). Sector C in Fig. 2 is probably the same for the climatic regions, and the most interesting for predictive modelling. It has the steppe stations, though there is no steppe zone on the geographical maps of Yakutia. The model has predicted all the locations of steppe in eastern Siberia (see Nazimova et al. 1990 for details).

A comparative analysis of mountain and plain forest zones (Figs. 1 and 2) leads to the conclusion that it is preferable to present the zonal forest formations of Siberia separately from the montane zones. In this way it is possible to get an informative and rather simple bioclimatic model fit to match the forest inventory data base and the meteorological station data base (Reference work 1966–1970).

In the bioclimatic graphic models (Figs. 1 and 2), each point of geographical space (meteorological station, for the sake of simplicity) is characterised by two major parameters of climate and, accordingly, by many features of the zonal ecosystem. The boundaries of the vegetation classes are empirical and static in ecological and may even find itself within a climatic area where all the forest formations and many of the tree species are at risk. These transition zones may be revealed and predicted by computerised map modelling. It should be mentioned that each zone is likely to be transformed according to landscape structure and biotic composition, and its track will be represented by tracks of all structural elements combining to form the zonal class. Fig. 3 demonstrates the Siberian plain meteorological stations in a parametric space of continental-warmth supply. One can see the less continental left part of this graphic portrait as being composed of dark-foliaged and pine forest types, the central part as being composed mostly of pine, and the rest as a continental part composed of larch. *Larix sibirica* replaces dark-foliaged forest types when Conard’s Cc is equal to 60–65, *Larix gmelini* replaces *L. sibirica* formation when Cc is close to 72, and *Larix cajanderi* becomes the absolute dominant forest species under the most continental climate (Cc = 85–100).

It is reasonable to dwell upon the continentality index Cc as one of few climatic indices predicted with more confidence. Continentality is an integrated expression of many critical weather conditions during the year; cloudiness regime, spring insolation, winter severity, hydrothermic regime of soils, etc. Thus, it could be regarded as a multidimensional sign. In continental Siberia with a broad range of Cc (50–100) it is less important than relative moisture. We suppose that for such a vast area as Siberia continentality is preferable as the first step of modelling, while relative moisture is the best for the next step.

The axis Cc makes it possible to distinguish...
sectors of climatic space close to West Siberian (WS continental humid), Central Siberian (CS extremely continental), and East Siberian (ES ultra and extremely continental). The sector CS varies from semi-humid (DI 1.4–1.0) to perhumid (DI 0.6–0.4) on some high watersheds. Also, the sector ES is not limited by one class of humidity and it was evaluated as being in the humid and semi-humid sector; in some cases even as being semiarid (DI close to 1.5–2.5).

Changes in tree species domination are marked from one sector to another and even within the same sector. The dependence on continentality of dark-foliaged forest has been mentioned earlier (Shumilova 1962, Sochava 1986). Extremely continental (Cc 70–80) and even ultra-continental (Cc 85–100) sector ES determines the dominance of the vast larch biome (cold-conifer-deciduous in the biome model of Prentice et al. 1992).

Tables of tree species ecological parameters are helpful in any study concerned with land cover prediction and forest management planning. Such tables have been made in 1985–1990 for thirty tree species. They have been partly published (Shugat et al. 1992), but the majority have not yet been published. The tables have special interest for the evaluation of resistance of natural forest stands to critical factors of climate as well as to some soil factors.

The approach suggested above is not map modelling, although our graphic models formed the basis for computerised maps and for a new version of the Siberian vegetation model (Tchekova et al. 1994). The Siberian vegetation model in its computerised map version has been successfully tested (Tchekhova et al. 1994) except for some discrepancies that appeared when the computerised maps were compared with conventional maps.

One of the reasons is the generalisation of the GDD 5 values for the northern border of the taiga in the Siberian computerised map model. As mentioned above, the limits of the forest species differ sufficiently. Larix cajanderi (Abaimov and Koropachinskii 1977), for example, is much more resistant to dry climate and frosty soils than is L. sibirica or Picea obovata, which form the northern forest boundary in western Siberia. The same discrepancies appear concerning the absolute values of the dryness index (DI) for the boundary between dark-foliaged and light-foliaged zonal formations in different sectors of continentality. It varies from 0.65 to 0.8 in West and Central Siberia, and tends to rise under extremely continental climate (Bukh et al. 1977). This is an additional argument for improving the Siberian vegetation model to take into account the sectoral differences in bio-climatic relations.

4 Conclusion

Our long-term study of the bioclimatic relations in Siberia has convinced us that the bioclimatic approach is valid not only for zones (sub-zones, altitudinal belts) but for Siberian tree species dominance, too. Many features of forest and non-forest ecosystems, including forest succes- sions, productivity, possible insect invasions, phytological characteristics, are reflected in multi-dimensional and two-dimensional climatic space. The continentality of the Siberian climate is one of the most important factors influencing land cover structure and its functioning. This parameter is preferable for zonal ecosystem modelling for the first step when broad-scale zonal classes are analysed.

The relative humidity of the climate is the main factor in zonal differentiation along with the supply of warmth at the next level of hierarchy. The landscape-ecological concept is preferable when studying forest lands. For a number of regions under investigation, the information content of graphic models could be markedly improved. Not only forest composition and productivity, but many other features of the vegetation and natural processes could be objects of prediction under the current climate. Among these features are landscape-forming forest types, pyrogenic and other successions, seasonal phenomena and processes, parameters of forest fire danger, biodiversity, etc. The zones do not look like uniform cells, but they may be presented as systems of fine-scaled units.

A new consideration concerning forest wildfires in Siberia is necessary in order to take into account the continental taiga. Fire is not only a factor disturbing forest ecosystems. Fires control to a large extent the forest ecosystem’s dynamics, natural species selection, biodiversity, and species competition. Many features of taiga structure and functioning are directly dependent on periodical fire events, which correlate with the main climatic characteristics of the soils.

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Postfire Recovery of Forest Litter in Scots Pine Forests in Two Different Regions of Boreal Zone

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Investigations carried out in the Kola peninsula (northern taiga) and in the South-western part of Western Siberia (southern taiga and forest-steppe) revealed identical course of the postfire restoration process of forest litter thickness in Scots pine forests. Despite the differences in mean annual temperature (2°C) and other climatic characteristics the recovery time for thickness of forest litter in both regions amounts to 90–100 years after fire in pine forests of lichen site type and 120–140 years – in green moss type; the thickness of forest litter therewith (3–4 cm and 7–8 cm respectively) that means that within the natural borders of pine forests, communities of a specific type possess uniform characteristics of restoration. On the basis of empirical data it appears that the predicted increase of mean annual temperature of earth surface by (2°C) will not bring changes into the character of postfire recovery of forest litter thickness. It was shown that during the period of the recovery, which spans about 90 years after fire in pine forests of lichen and green moss–lichen site types and 140 years in ones of green moss site types, the rate of increasing of carbon store in the forest litter averaged 0.6 t ha⁻¹ year⁻¹, 0.1 t ha⁻¹ year⁻¹ and 0.2 t ha⁻¹ year⁻¹, respectively.

Keywords: Scots pine forests, postfire recovery, forest litter

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