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

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A system of zonality 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 systematisation 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.

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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 (Prentice 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 (Prentice et al. 1992, Tchebakova et al. 1994). 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).

2 Materials and Methods

The study is based on voluminous empirical material and on long-standing observations of the climate (meteorological station data) and calculated climate indices for the belt boundaries in the mountains (Polikarpov 1966, 1970, Nazimova et al. 1981, 1990). Precipitation, warmth, and moisture indices were calculated with regional relationships with absolute height as well as the aspect and steepness of slopes (Sadovnichaya 1985, Tchebakova 1981,1983). For plains, we have calculated continentality indices for all weather stations involved in multi-dimensional analysis.

This work makes use of a few climatic indices and climatic ordination diagrams analysed from among a great number. The sum of active temperature (SAT) specifies the heat resources of climates in terms of plant requirements for active growth. It is defined as the sum of the mean daily temperatures above the threshold value of 10°C. It is preferable for comparative landscape-ecological analysis (Isachenko 1988). We used published data recorded at meteorological stations (Reference work ... 1966–1970). The SAT value does not coincide with the growing degree days (threshold value 5°C) (GDD) index. However, graphically they do correlate (Tchebakova et al. 1994). Dryness index (DI) (Budyko 1971) is the ratio of annual potential evaporation to annual precipitation (P). It was calculated by Tchebakova (see Tchebakova et al. 1994 for details). The continentality index (Cc) (Conrad 1947) is a function of the differences in July and January mean temperatures and latitude.

Among diverse indices, reflecting continentality, we took this parameter because it makes it possible to compare it with published data. This parameter reflects the annual replicability of oceanic and continental air masses and is important for the regions of Siberia and for Eurasia as a whole (Shumilova 1962, Sochava 1986, Tuhkanen 1984, Nazimova 1994).

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 dwindles under in cold climates. Mountain steppe and tundra also take their position and replace the oroboreal 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 semiarid larch-and-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, Buks 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 steppes 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 continentality 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-soil-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 bioclimatic 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 systematising 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

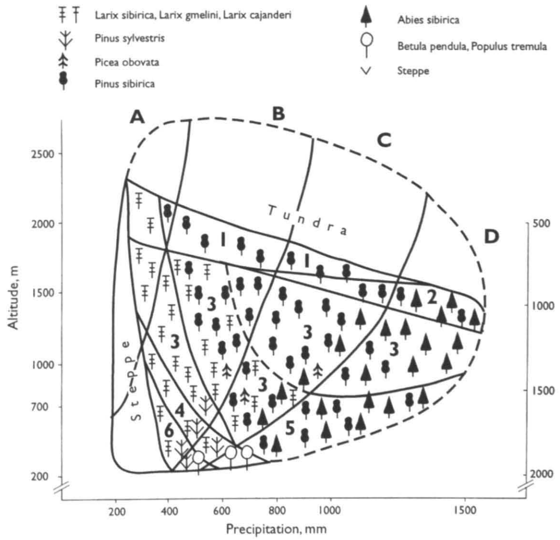

Fig. 1. The first conceptual model of the oroboreal forest. Altitudinal zones, biomes, and forest formations of South Siberian mountains in the climatic context: annual precipitation (Pmm) and active temperatures sum (T > 10) (Polikarpov & Nazimova 1976). 1 – Subgolets taiga (dark-foliaged) and larch 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). H, m – absolute height on 52°N–54°N. A, B, C, D – climatic facia of the oroboreal forest (spectra of altitudinal zones): 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 (Polikarpov 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 zono-biomes - 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 most resistant to high levels of radiation, to drought, and other stress factors.

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 1.2–0.9) 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 (oroboreal) 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 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 space. In short-term, and even long-term, successions they form a stable framework (constant). Vice versa, the points of geographical space could change their climatic co-ordinates.

The climate change modelled predicts new co-ordinates for each point in this parametric space. The point moves from one position to another 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 continentality-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 Conrad's Cc is equal to 60–65, *Larix gmelinii* 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).

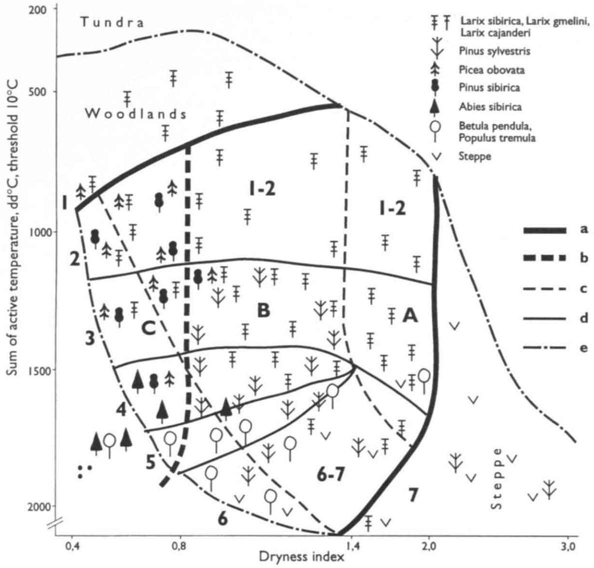

Fig. 2. Graphic model of zonobiomes and their subdivisions in Siberia along axes: Active temperature sum (t > 10°C and Dryness index DI). Zonobiomes: tundra, boreal forest (2–5), boreal and subboreal steppe (7). Zonoecotones: forest-tundra (1), forest-steppe (6). Boreal forest, sectors of humidity: A – light-foliaged cryo - semi-arid (*Larix gmelinii*, *L. cajanderi*); B – light-foliaged moderate humid and semi-humid (*L. sibirica*, *L. gmelinii*, *L. cajanderi*, *Pinus sylvestris*); C – dark-foliaged humid (*Pinus sibirica*, *Abies sibirica*, *Picea obovata*) and birch-pine semi-humid (*Pinus sylvestris*, *Betula pendula*). Forest zones and subzones: 2 – Northern taiga, 3 – Middle taiga, 4 – Southern taiga, 5 – Mixed birch – conifer subtaiga and "chern" forest with *Populus tremula*, *Abies sibirica* (denoted by dots in the left corner). Boundaries of: a) closed boreal forest, b) dark-foliaged subzones, c) sectors, d) termic subzones, e) real climatic space.

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 not 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

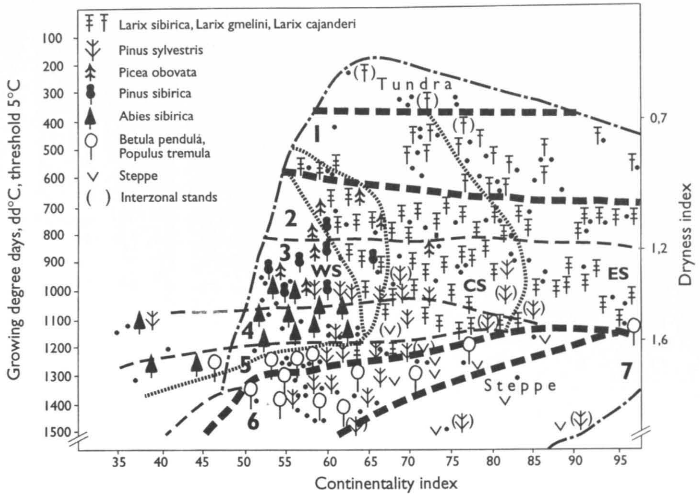

Fig. 3. Climatic ordination of meteorological stations (dots) and zonal forest types (signs) in Siberia. For conditional signs see Fig. 1, 2. GDD 5° – axes of heat supply, C. cont.– axes of continentality. 1,6 – zonoecotones forest-tundra and forest-steppe are cleared by bold dotted lines. Forest formations : i) *L. sib.*, *L. gm.*, *L. cj.* – larch forests with *Larix sibirica*, *L. gmelinii*, *L. cajanderi*. Sectors (groups of ecoregions): West Siberian continental humid and moderate-humid, CS – Central Siberian extremely continental humid and semi-humid, ES – East Siberian extremely and ultra-continental mostly semi-humid and semi-arid. ii) *P. slv.* – Scots pine forests (*Pinus sylvestris*), interzonal – in (), *P. ob.*– spruce forests (with *P. obovata*), *P. sib.* – *Pinus sibirica* forests, *A. sib.*, mixed – *Abies sib.* forests, and mixed, *B. p.*, *Pp. t.* – deciduous small-leaved forests with *Betula pendula*, *Populus tremula* (with no *Quercus* spp). St – steppe meteorological stations.

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 70–85) 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 (Shugart 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 (Tchebakova et al. 1994). The Siberian vegetation model in its computerised map version has been successfully tested (Tchebakova 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 is mentioned above, the limits of the forest species differ sufficiently. *Larix cajanderi* (Abaimov and Koropachinskyi 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 (Buks 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-termed study of the bioclimatic relations in Siberia has convinced us that the bioclimatic approach is valid not only for zones (subzones, altitudinal belts) but for Siberian tree species dominance, too. Many features of forest and non-forest ecosystems, including forest successions, productivity, possible insect invasions, pyrological 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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