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Stand Growth and Productivity of Mountain Forests in Southern Siberia in a Changing Climate

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Abstract

Local-level, bioclimatic regression models that relate stand characteristics (forest composition, height, site quality class and wood stocking) to site climate (temperature sums, base 5°C, and dryness index) were developed to predict the stand structure of dark-needled forest (*Pinus sibirica* and *Abies sibirica*) climax successions and their transformations in a changing climate over the Sayan mountain range in southern Siberia.

The models explained up to 80% of the variation in forest growth and productivity characteristics. Productivity varied widely and depended on heat supply rather than moisture. Stand tree species composition depended on moisture: dark-needled species and light-needled tree species (*Pinus sylvestris*) were separated by a dryness index value of 1.0. Living phytomass was calculated from a wood stocking model. Tree heights and living phytomass were mapped over the mountain range under current climate conditions and a regional climate change scenario. The model predicts that total dark-needled forest phytomass will decrease by 17% in a warmed climate.

Introduction

The mountain forests of southern Siberia are of special interest due to their high diversity and productivity and especially due to the most valuable tree species of the Siberian taiga - Siberian cedar (*Pinus sibirica*). Two main tree species, cedar and fir (*Abies sibirica*), dominate the mountain taiga forests on the windward northern and north-western slopes (Nazimova, 1975; Smagin *et al*., 1980). The climate of this region is moist, with annual precipitation varying from 500 mm at the lower elevation border of the cedar and fir forests to 1500 mm at their upper elevation border. The combination of sufficient heat supply and plentiful water favours the occurrence of forests composed of cedar and fir which are rich in biodiversity. These two species are called in Russian botanical and forestry literature 'dark-needled' tree species because of their high degree of shade tolerance. These forests were formed

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during the Holocene (Savina, 1986). Some relic species, such as the broadleaved tree species *Tilia cordata*, and groundcover species (e.g. *Asarum europaeum, Asperula odorata, Veronica officinalis, Dryopteris fillix-mas*) remain from the Tertiary in the lowland dark-needled (*'chern'* in Russian) forests which include various ferns and tall herbs. Chern forests covered vast areas of Siberia in the distant past (Shumilova, 1962). From the mid-1950s, cedar forests and especially productive chern forests underwent a significant decline due to intensive cutting. Since then, there have been many governmental decisions to organize sustainable forestry in these forests (Semechkin *et al*., 1985). Pine (*Pinus sylvestris*) forests, which dominate the subtaiga and forest steppe, are found only in a narrow band of the foothills on a flat, climatically homogeneous area (Smagin *et al*., 1980).

Evaluation of the forest stand transformations of a given site caused by both current land use and a changing climate can be performed by comparing current stand characteristics with those at climax stages. In many studies of mountain forests in southern Siberia, the climate was shown to be a principal environmental factor controlling forest composition and growth potential at the climax stage (Polikarpov, 1970; Polikarpov *et al*., 1986; Parfenova and Tchebakova, 2000). Stand models based on climatic parameters are the tools to employ to evaluate transformations caused by the climate. To our knowledge, no such stand models have been developed for these valuable mountain forests. Our goals were to build stand regression models that predict forest composition and productivity based on site climates and to apply these models to climate change scenarios in order to evaluate possible changes in forest structure and productivity on a local scale.

Methods

Quadratic regression models were developed that related the site climate of a plot and stand productivity characteristics of the forests along a transect in the Kulumys Range of the West Sayan mountains (93° E and 53° N), an area 30 km long and 20 km wide (Fig. 17.1).

Stand data for uneven-aged, mature stands only (older than 160 years for *P. sibirica* and 120 years for *A. sibirica*) at quasi-climax stages were derived from 412 inventory plots. Each stand was characterized by tree species composition (percentage of wood volume), average tree height (m) and trunk wood stocking (m^3/ha). Trunk wood stocking was analysed only for those stands which were 80% or more of one tree species. Additionally, stand living phytomass (t/ha) was calculated as a product of trunk wood stocking and the conversion coefficients representing ratios of the different stand fractions (bark, crown, roots and understorey) to the stem wood mass. The latter is calculated as a product of trunk wood volume and wood density. We derived appropriate conversion coefficients for our cedar and fir stands from Alexeyev and Birdsey (1998).

Two climatic indices - temperature sums, base 5°C (TS_5, heat supply), and a dryness index (DI, water supply) - were employed to characterize the site climate of a plot. In Russian climatology, temperature sums, base 5°C, are calculated as the sum of all positive temperatures (T) occurring for the period with daily temperature greater than 5°C:

$$TS_5 = \int T \, dt$$

integrated over the time period with $T > T_5$.

The dryness index is a ratio between available energy (radiation balance) and the energy required to evaporate annual precipitation. To calculate radiation balance,

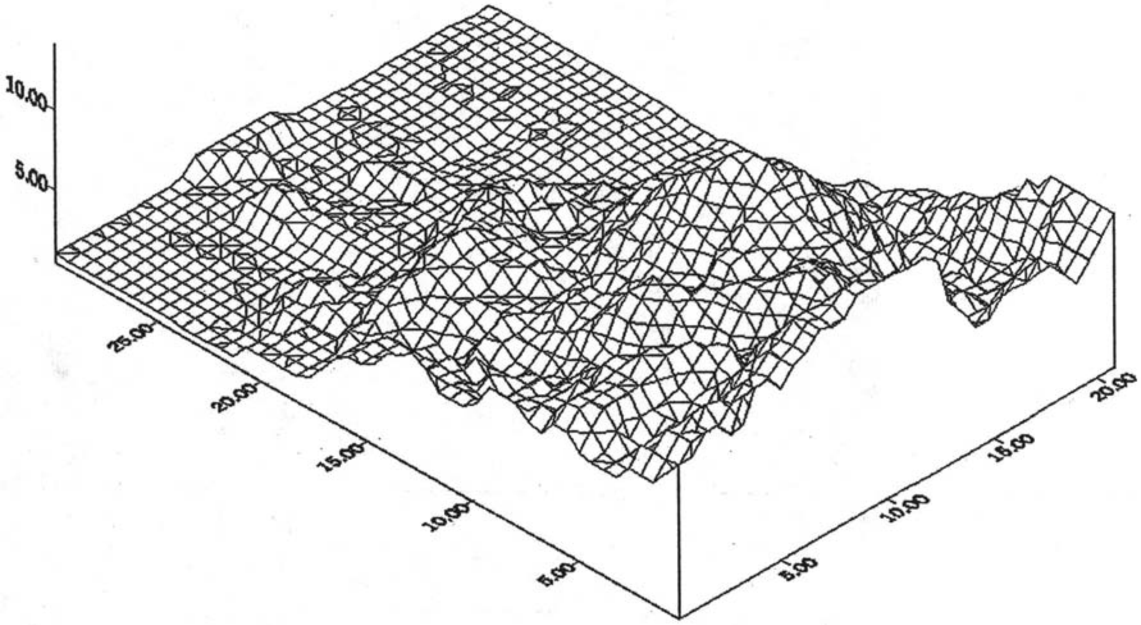

Fig. 17.1. A digital elevation model (m, *z* axis) of the test transect across the Kulumys Range, an area 20 km wide (*x* axis) and 30 km long (*y* axis).

data on temperature, humidity and cloudiness are required (Budyko, 1974; Tchebakova *et al.*, 1994). These climatic indices were calculated using the long-term climatic data of 10-15 weather stations adjacent to the test transect (Reference Books, 1967-1970). Climatic submodels relating TS_5 and DI to topography (elevation, slope and aspect when applicable) were developed to calculate climatic indices for each plot. Climatic submodels were coupled to a local digital elevation model (DEM) that we produced from a topographic map (1:100,000) to delineate current climatic layers of TS_5 and DI (Fig. 17.2a and b). With a regional climate change scenario of +1.5°C summer temperature and -4% summer precipitation (Hulme and Sheard, 1999), two new maps of climatic layers were recalculated by adding those departures to each pixel in the current climatic maps of TS_5 and DI. Stand models predicting tree heights and wood stocking were coupled with current and climate change TS_5 and DI layers to display heights and living phytomass over the test mountain range.

Results and Discussion

Stand models for predicting height, site quality class and wood stocking in cedar and fir forests along with some statistics are given in Table 17.1. Productivity characteristics were determined by a temperature factor, TS_5, with moisture, DI, being insignificant. The best fit of TS_5 to stand productivity characteristics was a quadratic regression with the argument expressed by the logarithm TS_5. The percentage of total variation explained for growth characteristics was as high as 80% for cedar stands and 40% for fir stands. It was less for wood stocking (Table 17.1).

In Fig. 17.3, the relationship between height and TS_5 is shown. On average, cedar trees are 8 m taller than fir trees. This difference is less in cold climates and greater in warm climates where cedar trees can grow to heights of 30 m or more. Although, on average, cedar trees are taller than fir trees, wood stocking of both fir

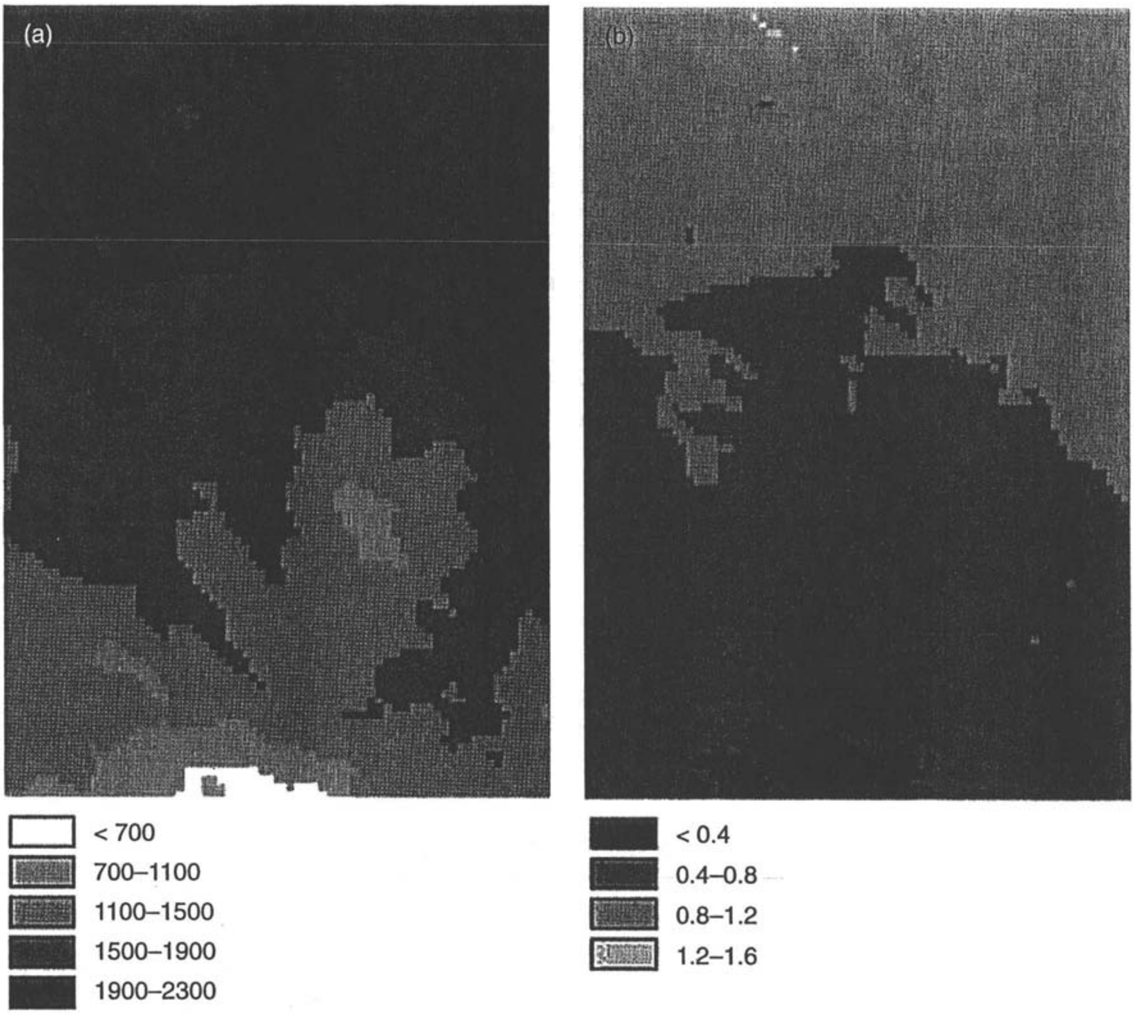

Fig. 17.2. Distribution of the current climatic layers of TS_5 (°C, a) and DI (dimensionless, b) over the study area.

Table 17.1. Stand models for predicting growth and productivity characteristics of the Sayan mountain forests. All regression coefficients were statistically significant at $P < 0.05$.

Stand parameter	Cedar stand models	Fir stand models
Height (m)	$-2508.70+1571.70*X-243.42*X^2$ $R^2 = 0.79$; SD = 4.3; $n = 233$	$-1729.99+1086.43*X-168.41*X^2$ $R^2 = 0.40$; SD = 3.6; $n = 272$
Wood stocking (m^3/ha)	$-48245.4+30504.5*X-4797.0*X^2$ $R^2 = 0.30$; SD = 72; $n = 184$	

X, log (temperature sums, base 5°C, TS_5); SD, standard deviation; n, sample size.

and cedar stands is about the same (Fig. 17.4) because the basal area of fir stands is usually greater than that of cedar stands (Nazimova, 1975). We developed a generalized wood stocking model for all stands regardless of forest composition. Wood stocking varied widely between 50 m^3/ha in highlands and 400 m^3/ha in lowlands.

Mountain forest composition of dark-needled stands along this transect was rather uniform. Because the ecology of cedar and fir is quite similar, these tree species compete for the same sites. Prevailing species occurrence depends on a forest succession stage rather than climate. As follows from the climatic ordination, DI

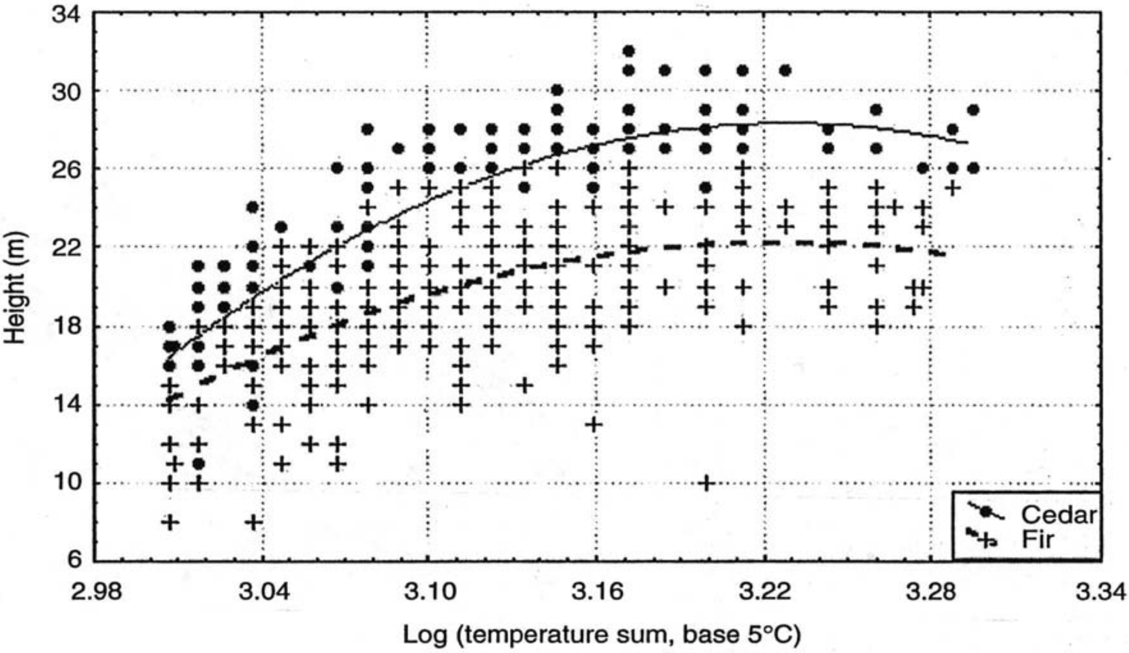

Fig. 17.3. Height (m) curves of cedar and fir depending on climate.

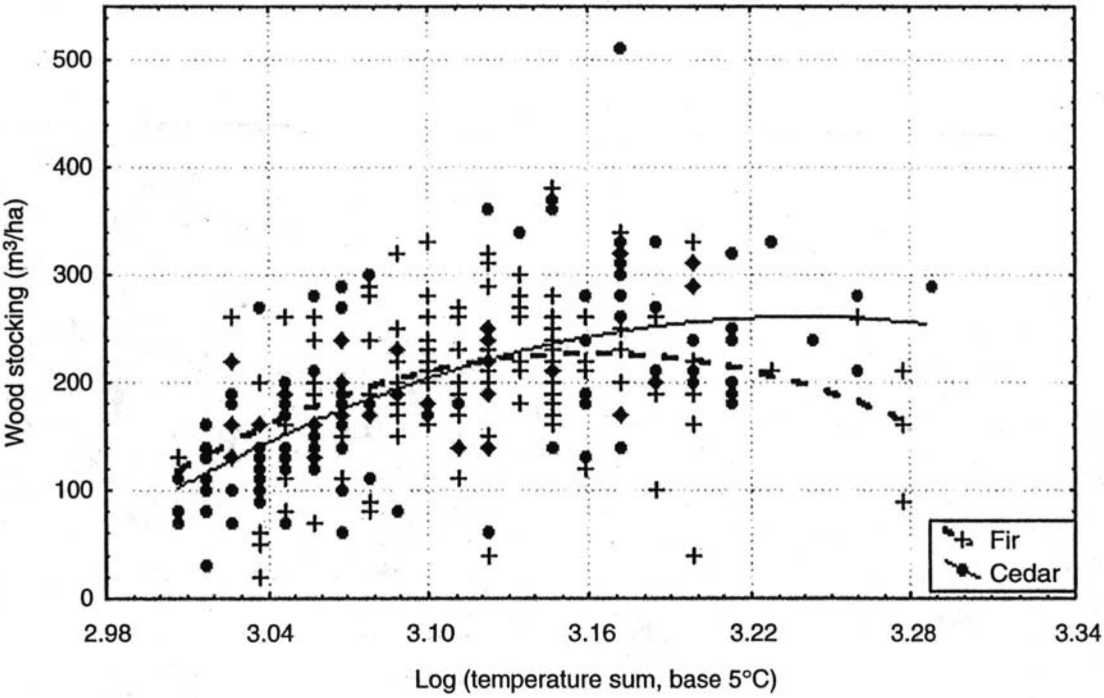

Fig. 17.4. Trunk wood stocking (m^3/ha) curves of cedar and fir depending on climate.

separated light-needled pine from dark-needled cedar and fir: light-needled pine had DI values above 1.0 while the others were below 0.8 (Fig. 17.5). This border is quite abrupt and clearly seen in forest maps.

Cedar and fir tree height distributions across the study area are shown in Fig. 17.6. Currently, more than a half of the study area is occupied by cedar stands with trees higher than 25 m and by fir stands with trees higher than 20 m. In a warmed climate, the area will be almost fully covered by forests with such tall trees. From our estimates, the tree line will shift some 250 m up-slope. Current treeless areas in

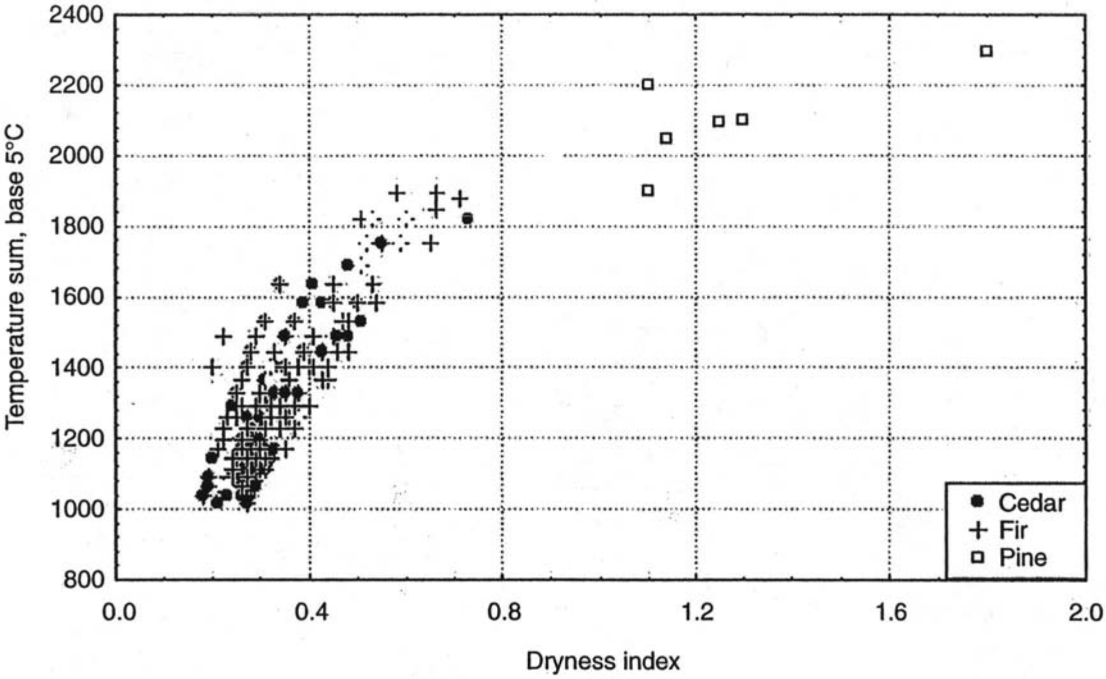

Fig. 17.5. Ordination of dominant tree species in climatic space.

highlands will be covered by forests with rather tall trees: 20-25 m cedar trees and 15-20 m fir trees. However, from our models we cannot say that trees could grow higher in a warmed climate than observed now. As seen from Fig. 17.3, in climates warmer than 1600°C of TS_5, heights of both tree species slowly start to decrease, because under these warmer conditions a greater than presently available water supply is required to favour tree growth. Tree growth in height may also be limited by species biology.

Living phytomass distribution calculated from the wood stocking model (Table 17.1) for the current and a warmed climate across a test transect is shown in Fig. 17.7. The data represented in the figures suggest that, under the current climate, less productive forests with a phytomass of <100 t/ha occupy only about 7% of the forest area. In general, the climate of this region favours productive cedar and fir forests with a phytomass >100 t/ha. In a warmed but drier climate, the area of these forests will decrease by about 8000 ha, which is about 20% of their current area. Dark-needled forests will shift up-slope by about 250-300 m. The pine subtaiga and forest-steppe area will increase by the same area correspondingly. Although most productive forests will dominate across this area, under warming the total forest phytomass will decrease by 0.8 Pg from 4.6 Pg today to 3.8 Pg in the future because their total area will decrease in lowlands.

Conclusions

The productive dark-needled forests of the Sayan mountains are of special interest both from the theoretical aspect of preserving biodiversity and from the forestry practices aspect of sustainable forestry. The climax growth potential of these forests and their structural changes in a changing climate can be evaluated by using bioclimatic models where forest characteristics are defined as functions of climate.

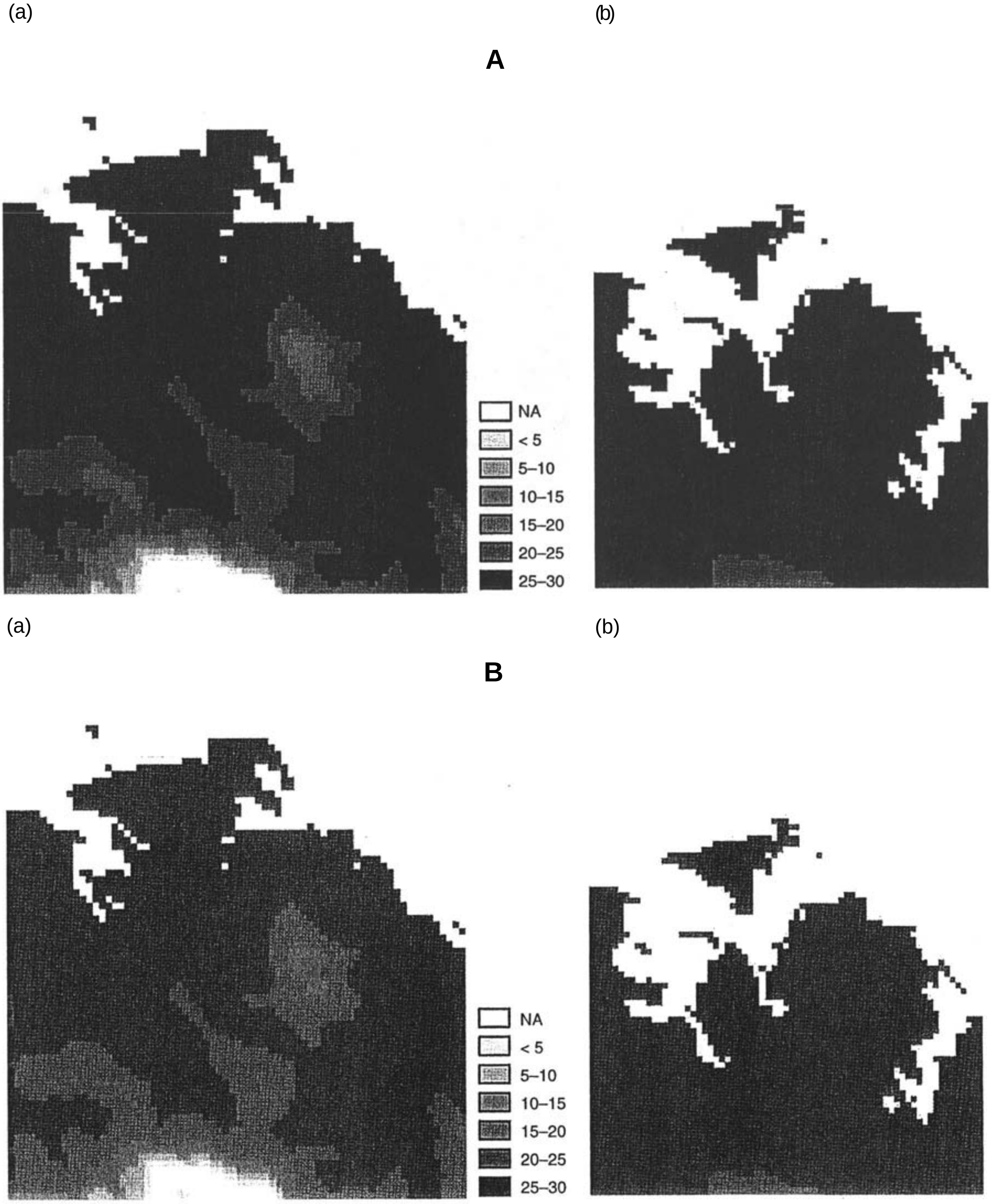

Fig. 17.6. Height (m) distributions for cedar (A) and fir (B) across the study area under current (a) and a warmed climate (b). NA means that a species is not available in a given pixel.

Bioclimatic stand models developed in this study allow us to evaluate growth and productivity characteristics from temperature parameters and tree species composition from moisture parameters. The dryness index separates the mountain, dark-needled (cedar and fir) forests and the light-needled, pine forests of the foothills by the dryness index value of 1.0. Because climates across the region are favourable for both cedar and fir, a dominant tree species in a stand is determined

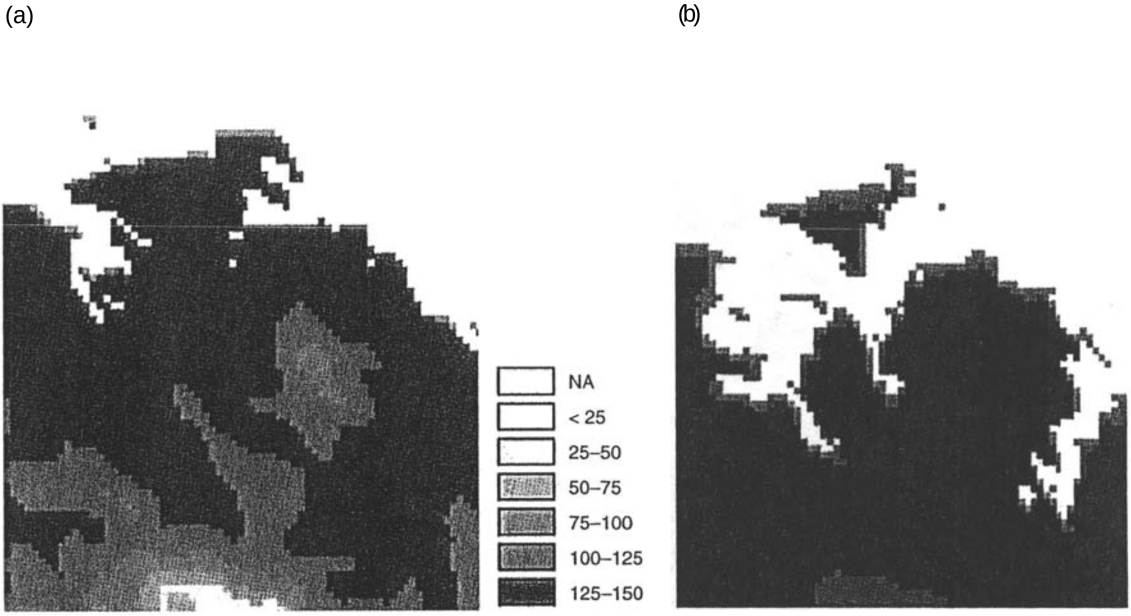

Fig. 17.7. Living phytomass (t/ha) of dark-needled forests across the study area under current (a) and a warmed climate (b). NA means that a species is not available in a given pixel.

by succession stage. The phases of cedar and fir forest successions caused by forest fires, droughts or insect pest outbreaks (Polikarpov, 1970) repeat in 200-250 years. Forest gap models (Shugart, 1984) may be used to specify the forest composition of these mixed cedar and fir stands at different succession stages.

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References

Alexeyev, V.A. and Birdsey, R.A. (eds) (1998) *Carbon Storage in Forests and Peatlands of Russia.* USDA Forest Service, Northeastern Research Station, General Technical Report NE-244, Radnor, Pennsylvania, 137 pp.

Budyko, M.I. (1974) *Climate and Life.* Academic Press, New York, 508 pp.

Hulme, M. and Sheard, N. (1999) *Climate Change Scenarios for the Russian Federation.* Climatic Research Unit, Norwich, 6 pp.

Nazimova, D.I. (1975) *Mountain Dark-needled Forests of West Sayan Mountains.* Nauka, Leningrad, 120 pp.

Parfenova, E.I. and Tchebakova, N.M. (2000) Possible vegetation change in the Altai mountains under climate warming. *Geobotanical Mapping* 1998-2000, 26-31.

Polikarpov, N.P. (1970) Complex investigations in mountain forests of West Sayan. In: Zhukov, A.B. (ed.) *Questions of Forestry,* Vol. 1. Institute of Forestry, Krasnoyarsk, pp. 26-79.

Polikarpov, N.P., Tchebakova, N.M. and Nazimova, D.I. (1986) *Climate and Mountain Forests of Southern Siberia.* Nauka, Novosibirsk, 225 pp.

Reference Books on Climate of the USSR (1964-1970) Issues: 17, 20-24. Gidrometeoizdat, Leningrad.

Savina, L.N. (1986) *Boreal Forests of Northern Asia during the Holocene.* Nauka, Novosibirsk, 192 pp.

Semechkin, I.V., Popova, Y.M. and Popov, V.E. (1985) Stand structure and productivity. In: Isaev, A.S. (ed.) Pinus sibirica *Forests of Siberia.* Nauka, Novosibirsk, pp. 117-132.

Shugart, H. (1984) *A Theory of Forest Dynamics: the Ecological Implications of Forest Succession Models.* Springer, New York, 278 pp.

Shumilova, L.V. (1962) *Botanical Geography of Siberia.* Tomsk University Press, Tomsk, 440 pp.

Smagin, V.N., Ilinskaya, S.A., Nazimova, D.I., Novoseltseva, I.F. and Cherednikova, J.S. (1980) In: Smagin, B.N. (ed.) *Forest Types of Mountains of Southern Siberia.* Nauka, Novosibirsk, 234 pp.

Tchebakova, N.M., Monserud, R.A. and Leemans, R. (1994) A Siberian vegetation model based on climatic parameters. *Canadian Journal of Forest Research* 24, 1597-1607.