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The 21st century climate change effects on the forests and primary conifers in central Siberia

Efectos del cambio climático del siglo 21 en los bosques y coníferas primarias en Siberia central

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SUMMARY

Regional studies have shown that winters warmed 2-3 °C while summers warmed 1-2 °C during the1960-2010 period in central Siberia. Increased warming predicted from general circulation models (GCMs) by the end of the century is expected to impact Siberian vegetation. Our goal is to evaluate the consequences of climate warming on vegetation, forests, and forest-forming tree species in central Siberia. We use our envelope-type bioclimatic models of the Siberian forests and major tree conifer species based on three climatic indices which characterise their warmth and moisture requirements and cold resistance, and on one soil factor that charactrises their tolerance to permafrost. Coupling our bioclimatic models with the climatic indices and the permafrost distributions, we predict the potential habitats of forests and forest-forming tree species in current climate conditions and also in the 2080 projected climate. In the 2080 drier climate conditions, Siberian forests are simulated to decrease significantly and shift northwards while forest-steppe and steppe would come to dominate 50 % of central Siberia. Permafrost is not predicted to thaw deep enough to sustain dark (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*) taiga. Dahurian larch (*L. gmelinii+cajanderi*), which is able to withstand permafrost, would remain the dominant tree species. Light conifers (*Larix spp*. and *Pinus sylvestris*) may gain an advantage over dark conifers in a predicted dry climate due to their resistance to water stress and wildfire. Habitats for new temperate broadleaf forests, non-existent in Siberia at present, are predicted by 2080.

Key words: climate warming, bioclimatic models, major conifer ranges, Central Siberia.

RESUMEN

Estudios regionales muestran que los inviernos se han calentado de 2 a 3 ºC mientras que en los veranos se reportan alzas de 1 a 2 ºC entre 1960 y 2010 en Siberia Central. El aumento del calentamiento predicho por modelos de circulación general (GCMs) para el fin de este siglo impactaría la vegetación en Siberia. El objetivo del estudio fue evaluar las consecuencias del calentamiento climático sobre la vegetación, los bosques y las especies arbóreas de Siberia central. Se usaron los modelos bioclimáticos de tipo envolvente de los bosques siberianos y las especies de coníferas más importantes, basados en tres índices climáticos que caracterizan sus requerimientos de calor y humedad y resistencia al frio, y en un factor de suelo que caracteriza su tolerancia al permacongelamiento. Acoplando los modelos bioclimáticos con los índices climáticos y la distribución del permacongelamiento, se pudo predecir los hábitats potenciales de bosques y las especies arbóreas bajo las condiciones climáticas actuales y para las condiciones climáticas al año 2080. Bajo las condiciones climáticas más secas del año 2080, se predice que los bosques siberianos decrecerán significativamente y se desplazarán hacia el norte mientras que los bosques esteparios y la estepa dominarán el 50 % de la superficie de Siberia Central. Se predice que el permacongelamiento no se derretirá a niveles tan profundos suficientes para sostener la taiga oscura (*Pinus sibirica*, *Abies sibirica* y *Picea obovata*). El alerce dahuriano (*L. gmelinii+cajanderi*) que es capaz de soportar permacongelamiento, permanecerá como la especie dominante. Las coníferas de luz (*Larix spp*. y *Pinus sylvestris*) pueden ganar ventaja sobre las coníferas oscuras en un clima más seco debido a su resistencia al estrés hídrico y los incendios. Para el 2080 se predice el surgimiento de hábitats para los nuevos bosques templados latifoliados, no existentes actualmente en Siberia.

Palabras clave: calentamiento climático, modelos bioclimáticos, rangos mayores de coníferas, Siberia central.

INTRODUCTION

Regional studies in Siberia have already registered a change in climate at the end of the 20th century (Soja *et al*. 2007, Tchebakova *et al*. 2011ab). A mounting body of evidence of the changes in Siberian vegetation and in the forests in particular related to climate warming is available in the literature and summarized in the reviews of Soja *et al.*(2007) and Tchebakova *et al.* (2011a). At the northern treeline, the forest has shifted into tundra and open forests have become more stocked. Within the permafrost zone, which is dominated by only *Larix dahurica* P. Lawson, an undergrowth of dark conifers like Siberian cedar (*Pinus sibirica* Du Tour), fir (*Abies sibirica* Ledeb.), and spruce

(*Picea obovata* Ledeb.) up to 40-years-old is found because of an active layer depth recently increased in a warming climate. Upper treeline shifts of 40-100 m upslope is registered in the mountains in the south: Altai, Kuznetsky Alatau, West Sayan, and even in the north in the Putorana Plateau. At the lower treeline in the West Sayan, the *Pinus sibirica* seed production is significantly decreased for 1990-1999, the warmest decade of the last century, which may cause changes in the forest structure. Foresters presumably explain this fact by an increased probability of the cone damage done by the moth *Dioryctria abietella* (Denis *et* Schiffermüller) (Lepidoptera: Pyralidae (Phycitinae)). This moth is recently found to produce two generations within a single longer growing season observed under climate warming.

In this study, using IPCC (Intergovernmental Panel on Climate Change) climate change projections, we hypothesize what large-scale potential effects of climate change we may expect on vegetation, forests, and forest-forming conifers by the end of the 21st century within the Krasnoyarsk territory in central Siberia. To reach this goal, we couple our bioclimatic models of the Siberian forests and major tree conifer species with these IPCC projections to predict their potential distribution in 1960-1990, from historical climate data, and in a changed climate by 2080, from GCM (General Circulation Models)-predicted data.

Figure 1. Study area in central Siberia (black) with locations of 80 weather stations used in the study on the background of the former Soviet Union.

Área de estudio en Siberia central (negro) con la ubicación de 80 estaciones climáticas sobre el mapa de la anterior Unión Soviética.

METHODS

The study area is the vast Krasnoyarsk territory and adjacent Republic of Khakassia to its south (figure 1). The territory stretches from the Arctic seas to the Mongolian border for about 2,500 km and is 10 -fold larger than Great Britain, 4.5-fold larger than France, and 3-fold larger than Chile (Ushakova 2006). The territory crosses different vegetation zones from Arctic tundras in the north southwards to taiga (northern, middle and southern), subtaiga, forest-steppes, and steppes, respectively. The change in climate across the study area at the turn of the 21st century was calculated from the data from 80 weather stations within the study area (figure 1). Climate change was considered for three climatic variables: winter and summer thermal conditions (January and July temperatures) and annual precipitation. Change for all three variables was calculated from differences (departures) between the means of the 30-year baseline period 1961-1990, the means of the historic period 1990-2010, and the GCM-modeled period 1990-2080 (figure 2). Departures of both temperatures and precipitation for 1990-2010 from the basic period 1960-1990, as evaluated by the Student criteria, were statistically significant at the level of 0.02. Then, July and January temperatures and annual precipitation were used to calculate climatic indices ecologically important for vegetation: growing degree-days, base above 5 ºC, GDD_5, and negative degree-days below 0 ºC, NDD_0, characterizing warmth requirements and cold resistance, and an annual moisture index, AMI, the ratio of GDD_5 to annual precipitation characterizing resistance to water stress.

We used our SiBCliM (Siberian bioclimatic model) (Tchebakova *et al.* 2009), a static envelope-type large-scale bioclimatic model based on the vegetation classification of Shumilova (1962) in our calculations. SiBCliM simulate Siberian zonal vegetation and forests from three bioclimatic indices: GDD_5, NDD_0, and AMI, uniqely limiting each vegetation class. The bioclimatic limits within the model were derived from the ordination of 150 weather stations each of which was characterised with a given vegetation class in axes of the GDD_5, NDD_0, and AMI indices (Tchebakova *et al.* 2003). SiBCliM separated vegetation and forests by GDD_5 into latitudinal subzones from north to south: tundra; forest-tundra; northern, middle and southern taiga; and forest-steppe. The AMI separates vegetation into two large types**,** forest and steppe, and further subdivides the forest into dark (shade-tolerant and water-loving *Pinus sibirica*, *Abies sibirica*, and *Picea obovata*) and light (shade-intolerant and water-stress resistant *Pinus syvestris* L. and *Larix spp.*) according to Russian geobotany classifications. NDD_0, equal to -3,500-4,000 °C, corresponded well to the permafrost border and also tended to separate dark and light-needled conifers. Four temperate vegetation classes (broadleaf forest, forest-steppe, steppe, and semi-desert/desert) that do not exist in the current Siberian climates were included in SiBCliM because of their potential importance in future climates. Therefore, in total, the current version of SiBCliM included 14 vegetation classes: ten boreal and four temperate vegetation classes.

The forests across Siberia consist largely of eight conifers (Pozdnyakov 1993): about 50 % *Larix spp.* (four species), 13 % *Pinus sylvestris*, 7 % *Picea obovata*, 6 % *Pinus sibirica*, and 2 % *Abies sibirica*. Climate envelopes of GDD_5, NDD_0, and AMI for each conifer were found using gene-ecological studies (data of about 250 provenances

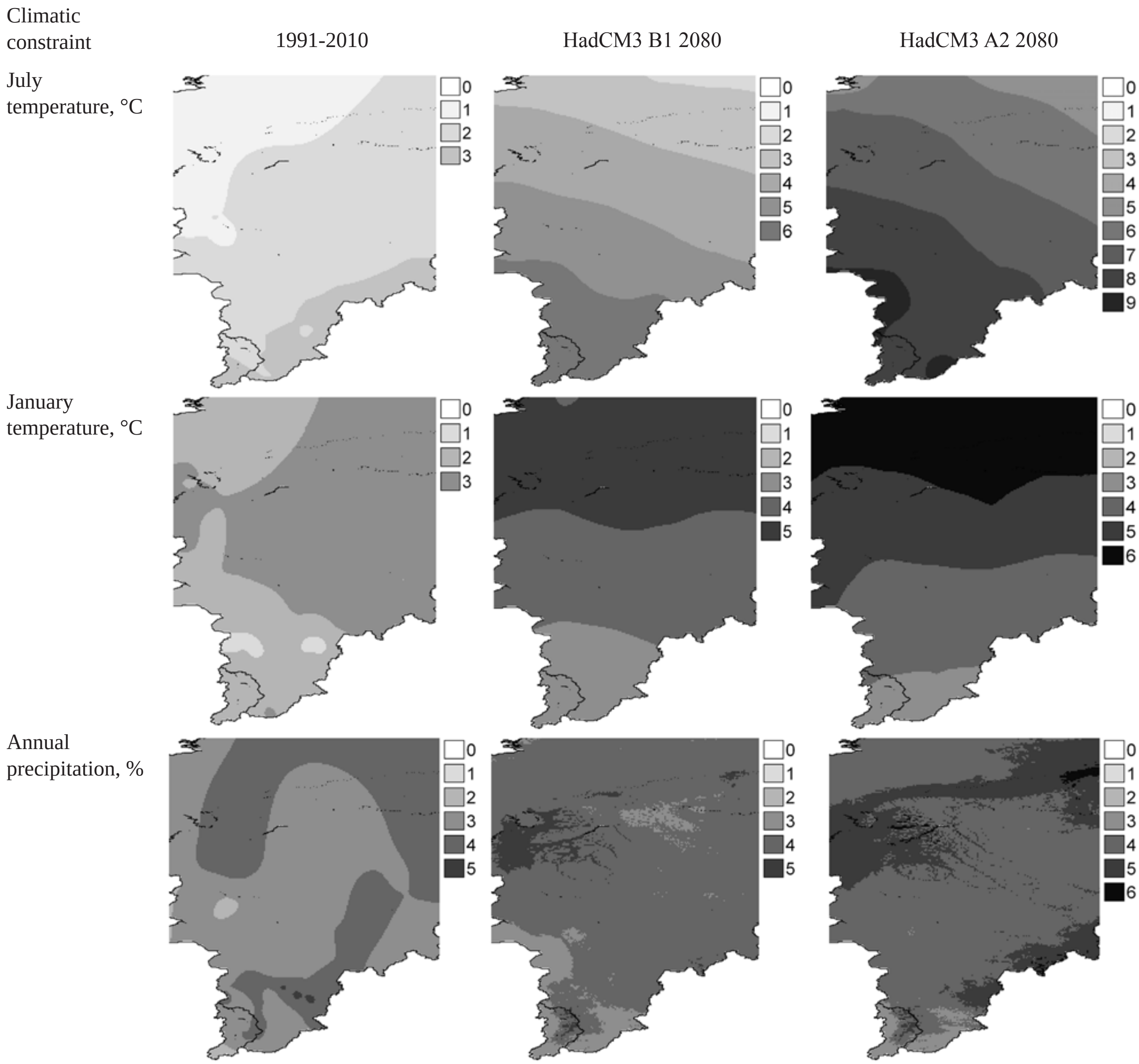

Figure 2. Departures of July and January temperatures and precipitation across central Siberia in 1991-2010 relative to the baseline period, 1961-1990, calculated from historic data (left) and those derived from the HadCM3 B1 (center) and A2 (right) 2080 climate change projections. Scale: 0 – beyond the study area; 1 – 1 °C, 2 – 2 °C, 3 – 3 °C, 4- 4 °C, 5 – 5 °C, 6 – 6 °C, 7 - °C, 8 – 8 °C, 9 – 9 °C.

Temperaturas y precipitaciones de julio y enero a lo largo de Siberia central para el periodo 1991-2010 en relación al periodo base 1961-1990, calculadas a partir de datos históricos (izquierda) y aquellos derivados de las proyecciones de cambio climático bajo HadCM3 B1 (centro) y A2 (derecha). Escala: 0 – fuera del área de estudio; 1 – 1 °C, 2 – 2 °C, 3 – 3 °C, 4- 4 °C, 5 – 5 °C, 6 – 6 °C, 7 -7 °C, 8 – 8 °C, 9 – 9 °C.

for *Pinus sylvestris* and 150 for *Larix spp*., Rehfeldt *et al.* 1999, 2002), the climate estimated for extreme locations on range maps, and various publications (Tchebakova *et al.* 2003, 2006).

No soil conditions except presence/absence of permafrost were taken into account in SiBCliM. Permafrost, occurring on 80 % of Siberia, is an important ecological factor controlling the contemporary vegetation distribution across Siberia (Shumilova 1962, Pozdnyakov 1993). The active layer depth (ALD), a portion of thawed permafrost, equal to 2 m, calculated from the above climatic indices GDD_5, NDD_0 and AMI ($R^2 = 0.7$), was substituted for the permafrost border in SiBCliM. ALD > 2 m explicitly allowed all conifers to thrive, and ALD < 2 m allowed only one conifer *Larix dahurica* Turcz. (*L. gmelinii* (Rupr.) Rupr. + *L. cajanderi* Mayr.) that could withstand lower ALD to grow (Pozdnyakov 1993).

Kappa (K) statistics (Monserud and Leemans 1992) were used to compare both the modeled vegetation and the conifer distributions in Siberia in the contemporary climate to the actual map of Isachenko *et al.* (1988) and the "Forests of the USSR" map of Isaev *et al.* (1990).

Each forest type and conifer distribution from 1960-1990 to 2080 was mapped by coupling our bioclimatic models with bioclimatic indices and the permafrost distribution for the basic period and 2080 simulation. Climatic departures for the 2080 climate were derived from two climate change scenarios, the HadCM3 A2 and B1 (IPCC 2007), reflecting the largest and the smallest temperature increases: up to 9 °C and to 4-5 °C in summer and > 9 °C and 6-7 °C in winter.

RESULTS

Tchebakova *et al*. (2011ab) demonstrated climate warming over the last half century from 1961 to 2010 in central Siberia. Our analysis proved that for 1991-2010, when compared to the basic 1961-1990 time period, winters became 2–3 °C warmer in the north and 1–2 °C warmer in the south by 2010. Summer temperatures increased by 1 °C in the north and by 1–2 °C in the south. Change in precipitation was more complicated, increasing on average by 10% in middle latitudes and decreasing 10–20 % in the south, promoting local drying in already dry landscapes (figure 2).

The comparison between our modeled and the real (Isachenko 1988) vegetation maps showed that the overall agreement was "fair" (K = 0.53) and agreements by separate vegetation classes showed from "exellent" (K > 0.7) to poor (K < 0.4) matches across Siberia (Tchebakova *et al.* 2009). Thus, K-statistics proved that SiBCliM accomplished a fair work in modeling Siberian vegetation. Simulations indicated that vegetation would be severely altered by 2080: a moderate change in vegetation was predicted from the B1 scenario, but dramatic changes were predicted from the A2 scenario (Tchebakova *et al.* 2009). The forest zones could shift northwards as far as 600-1,000 km by substitution or complete replacement of the northern ecosystems (tundra, forest-tundra). Siberian forests would decrease and forest-steppe, steppe ecosystems, and even semidesert/desert were predicted to dominate 50 % of central Siberia due to the 2080 drier climate. Despite the predicted large increases in warming, permafrost was not predicted to thaw deep enough to sustain dark (*Pinus sibirica*, *Abies sibirica*, and *Picea obovata*) and light (*Larix sibirica* and *Pinus sylvestris)* taiga. *Larix dahurica* taiga was predicted to continue to be the dominant zonobiome because of its ability to withstand continuous permafrost. SiBCliM also predicted temperate broadleaf forest (with *Tilia sibirica* Bayer) and forest-steppe habitats in the south, which are non-existent today.

The tree species distribution across central Siberia is shown in figure 3. Comparison of conifer distributions on real and modeled (figure 3) maps showed a fair agreement. Any climate-modeled tree range is a potential one because it does not consider soil or phytosocial (competition) and disturbance factors, so a potential range is always larger than a real range. Thus, 73 % of the real *Pinus sibirica* range (figure 3: 1A), 34 % of the *Abies sibirica* range (figure 3: 2A), 64 % of the *Pinus sylvestris* range (figure 3: 3A), and 46 % of the *Larix sibirica* and *L. gmelini* range (figure 3: 4A) were within their climatic potential ranges (figure 3: 1-4B). Those matches might be higher because historically part of the primary conifer forests were replaced by secondary birch and aspen forests after large disturbances (clearcuts and wildfire).

During the 21st century, with the warming and drying climate, habitats should become increasingly more suitable for drought-resistant light conifers: two times larger for *Pinus sylvestris* (figure 3: 3C) and 10 % larger for the *Larix* genera as a whole (figure 3: 4C). However, permafrost will not thaw deep enough to support Siberian conifers requiring 1-2 m of ALD. *Larix dahurica*, which can withstand the shallow ALD, would still dominate most Siberian taiga. Habitats for dark conifers, *Pinus sibirica* and *Abies sibirica* (figure 3: 1C and 2C), would shrink about 1.5-2-fold and shift north- and northeastward as far as 600 km by 2080. Their distribution will be limited by the permafrost border in the north and the drying climate in the south.

DISCUSSION AND CONCLUSIONS

Natural climate-change-caused disturbances (weather, wildfire, infestations) and antropogenic disturbances (legal/illegal cuttings) have increased their impacts on the boreal forest in Siberia for the last three decades (Pleshikov 2002, Soja *et al.* 2007). Permafrost melting initiates thermokarst and solifluction processes across broad expanses of Siberia thereby disturbing forest landscapes (Abaimov *et al.* 2002). With the retreat of permafrost, forests would decline in extent due to lack of moisture in interior Siberia and be replaced by steppe in well-drained areas or by bogs in poorly drained areas (Tchebakova *et al.* 2009). Based on the analyses of the transient effects of climate change on the circumboreal biosphere, Soja *et al*. (2007) suggest a potential non-linear, rapid response of the boreal ecosystem to changes in climate vs the expected slow linear response.

Fire and permafrost are considered to be the principal mechanisms affecting the forest's range and structure (Polikarpov *et al.* 1998). Predicted warm and dry climates enhance the risks of high fire danger and thawing permafrost, both of which challenge contemporary ecosystems. The northern treeline shift is dependent on tree migration rates, permafrost retreat rates, and soil suitability for the future forests. Current estimates, however, suggest that due to low natural migration rates, forest zones and tree species shifts will require long periods to adjust to the great amount of predicted climate change. However, developing management strategies for seed transfer to locations that are best ecologically suited to these genotypes in future climates could be man's contribution toward assisting

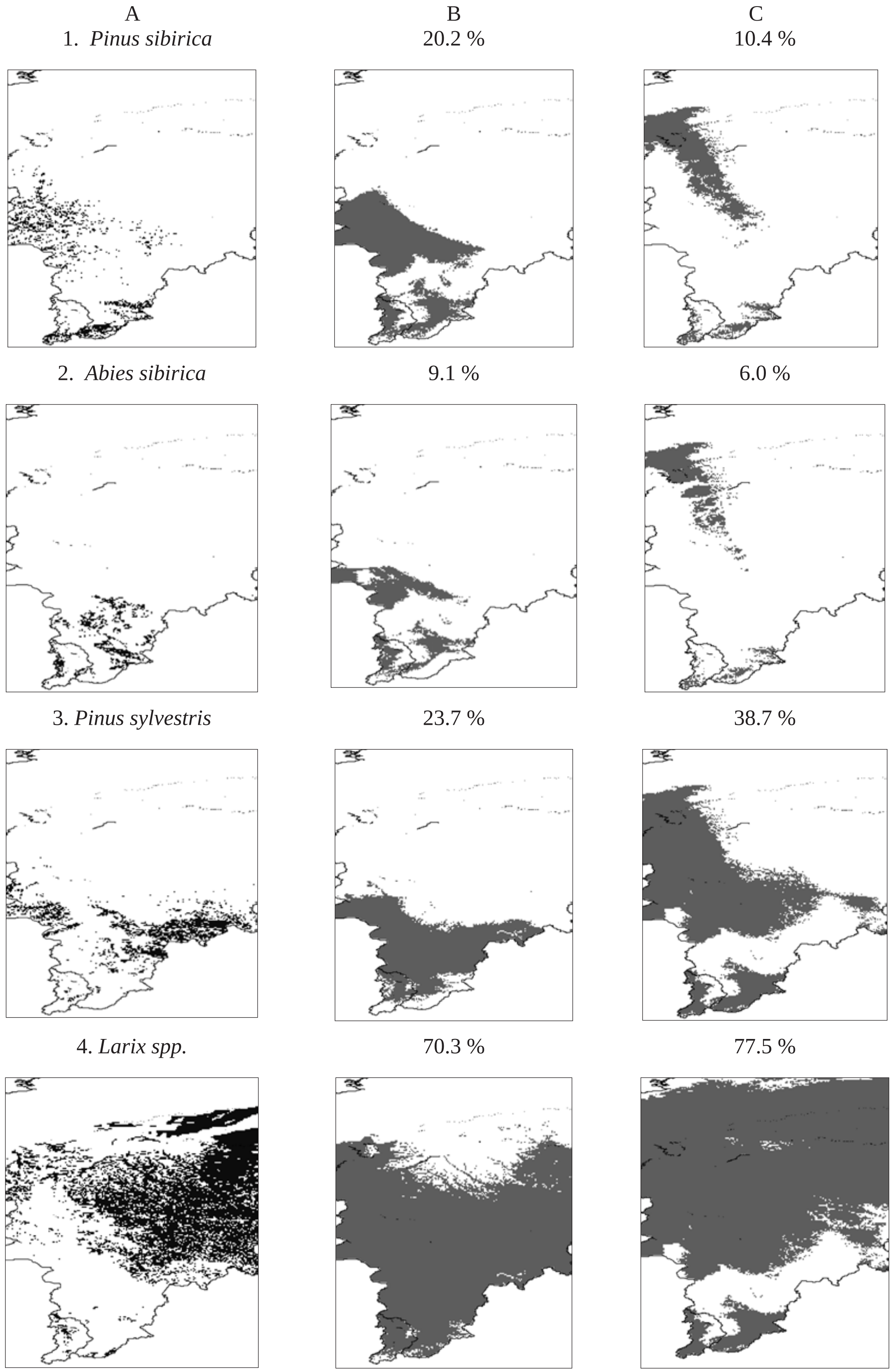

Figure 3. Major conifer conifer distributions: in Isaev et al. (1990) map (1-4 A), modeled (% of the total area) in current climae (1-4 B) and in the 2080 HadCM3 A2 climate (1-4 C).

Distribución de las principales coníferas: en el mapa de Isaev et al. (1990) (1-4 A), modelado (porcentaje del área total) para el clima actual (1-4 B) y para el clima de 2080 HadCM3 A2 (1-4 C).

trees and forests to be harmonized with a changing climate (Rehfeldt *et al*. 1999, 2002).

The southern treeline shift is controled by fire. In the last two decades extreme fire seasons have significantly increased in Siberia (Soja *et al*. 2007), and catastrophic fire frequency has increased to once in 10 years (Shvidenko *et al.* 2011). Due to an increased forest fire frequency and shorter fire return intervals, forest regeneration may not be possible in a hotter and drier climate or if possible, may not survive the forest establishment stage. Frequent fires may also change the forest structure. The fire return interval in the light conifer (*Larix spp*. and *Pinus sylvestris*) middle taiga in central Siberia is currently 20-30 years (Furyaev *et al.* 2001) compared to 200-300 years in the dark conifer (*Pinus sibirica* and *Abies sibirica*) southern and mountain taiga in southern Siberia (Polikarpov *et al*. 1998). After fire events, slowly growing dark conifers, not adapted to frequent fires, typically die; both larch and pine, evolutionarily adapted to fire, successfully regenerate after fire events. While adaptation of the forests and tree species to climate change at the range boundaries would occur by means of migration (Kirilenko and Solomon 1998), within the forest ranges the genetic means are considered the principal means of adaptation (Rehfeldt *et al*. 2002).

Our envelope-type vegetation and forest models are based on climate-vegetation classifications. This approach is best-known and simplest to predict the equilibrium response of vegetation to climate change. However, the major disadvantage of this type of models is that vegetation/forest types will not change and shift as a whole under climate change in the future. The vegetation/forests are made up of a number of species which will individually respond to a changing climate and may compose not only known but also unknown vegetation/forest types (Peng 2000).

Our simulations of the forests and forest-forming conifers in central Siberia demonstrate the profound effects of the GCM-predicted climate change on the ecological distribution of future forests. Forest analogs (tree species composition) to the future forests of Siberia exist contemporarily, thus, we can assume that the forests are capable of adjusting to the predicted environmental change. Light conifers may have an advantage over dark conifers in a predicted dry climate and may cover a larger area in the near future due to their stronger resistance to water stress and wildfire. SiBCliM also predicted new habitats suited to temperate vegetation (broadleaf forest and forest-steppe) in the south by 2080.

Evidence of changes in the Siberian taiga structure and shifts in treeline in central Siberia are available in the literature. Kharuk *et al.* (2005) show that in Evenkia (Central Siberian Tableland) undergrowth of *Pinus sibirica, Picea obovata,* and *Abies sibirica,* which are not currently found on cold permafrost soils are now emerging in the *Larix gmelinii* taiga, possibly due to the increased depth of ALD that allows for the survival of dark-needled seedlings. Strong evidence treeline shifts of 50-120 m during a 50-year span in the mid-20th century is derived *in situ* in the southern mountains in central Siberia (for more details see Soja *et al.* (2007) and Tchebakova *et al.* (2011a).

Principal forest ecosystem services would be altered under climate change impacts. The ecosystem services in mountain forests in the southern Siberia are predicted as follows: both demand and supply of provisioning of timber and firewood would remain the same; both demand and supply of carbon sequestration would increase; demand for prevention of wildfires would increase while the supply of service would worsen; demand for maintaining natural habitats for biodiversity would increase while the supply would worsen; both demand and supply for the provisioning of fresh water would increase; both demand and supply of the provisioning of land and conditions for farming would improve (Gerasimchuk 2011).

The establishment of agricultural lands may appear in new forest-steppe and steppe habitats because the forests would retreat northwards. Currently, food, forage, and biofuel crops primarily reside in the steppe and forest-steppe zones which are known to have favorable climatic and soil resources. During this century, traditional Siberian crops could be gradually shifted northwards and new crops, which are currently non-existent but potentially important in a warmer climate, could be introduced in the extreme south (Tchebakova *et al.* 2011b). Desertification is expected in some extreme southern Siberian areas as a result of decreased precipitation and dramatically increased temperatures.

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