

Large-scale treeline changes recorded in Siberia

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[1] Analysis of a multi-species network of western Siberian ecotone sites revealed pulses of tree invasion into genuine treeless tundra environments in the 1940s and 1950s and after the early 1970s. In addition, increases in radial stem growth synchronous to the late 20th century treeline change are observed. Both treeline changes and growth increases correspond with decadal-scale periods of temperature that are warmer than in any other period since observations started, suggesting - even if indirect - the sensitivity of large-scale treeline changes to this climatic forcing. The mid 20th century recruitment period reported here for the western Siberian network is compared with local findings from Europe and North America suggesting a circumpolar trend perhaps related to climate warming patterns. For western Siberia, the presence of relict stumps, nevertheless, indicates that this present colonization is reoccupying sites that had tree cover earlier in the last millennium. **INDEX TERMS:** 1620 Global Change: Climate dynamics (3309); 1630 Global Change: Impact phenomena; 9315 Information Related to Geographic Region: Arctic region. **Citation:** Esper, J., and F. H. Schweingruber (2004), Large-scale treeline changes recorded in Siberia, *Geophys. Res. Lett.*, *31*, L06202, doi:10.1029/2003GL019178.

1. Introduction

[2] 20th century warming patterns have been demonstrated to affect the photosynthesis [Lucht *et al.*, 2002] and growth rate [Esper *et al.*, 2002] of forest ecosystems. Instrumental temperature records show and models predict some of the greatest warming in the Northern Hemisphere land areas covered by the treeline tundra-taiga ecotone [Hansen *et al.*, 1999; Jones *et al.*, 1999]. This ecotone is an ecological boundary that evolves from the interaction between environmental conditions and vegetation itself [Arno and Hammerly, 1984]. At more local scales tree recruitment is related to some combination of temperature variations, micro-site conditions, insect outbreaks, winter-time snow and wind conditions and grazing pressure [Holtmeier, 2000; Payette, 1974; Payette and Filion, 1985; Stöcklin and Körner, 1999]. Nevertheless, it has been argued that growing season temperature alone determines global treeline limits [Brockmann-Jerosch, 1919; Körner, 1998].

[3] Focusing on the temporal dynamics of subarctic treelines, several dendroecological studies, including comparisons of repeated photographs and studies of tree growth forms, have revealed treeline positional and structural changes during the 20th century in Scandinavia [Aas,

1969; Hofgaard *et al.*, 1991; Hustich, 1958; Kullmann, 1986], the Polar Urals [Gorchakovskiy and Shiyatov, 1978; Shiyatov, 1992], Quebec [Lavoie and Payette, 1994; Payette *et al.*, 1985], and in the Canadian Rocky Mountains [Luckman and Kavanagh, 1998], for example. However, the observations from these Northern Hemisphere subarctic treeline sites vary: in some cases, the local treelines have advanced, whereas in other cases they have remained static.

[4] In this study we aim to overcome some of the limitations typical to local approaches and analyze treeline dynamics over western Siberia during the 20th century by comparing nine undisturbed polar sites located between 59°–106°E (~1900 km) and 61°–72°N (~1100 km, Figure 1). However, this large-scale approach precludes detailed ecological and environmental justification of treeline dynamics as, for example, long-term local forcing data are broadly lacking. Nevertheless, by merging the information from nine sites, larger-scale patterns of treeline changes are demonstrated, and related to decadal-scale temperature variations. Current treeline positions are also related to former treeline extension by documenting in-situ remnants of relict stumps and logs.

2. Treeline Sampling Strategy

[5] To quantify treeline dynamics we used the following sample site properties:

[6] (i) The germination ages of 276 trees, dated by counting the annual stem growth rings,

[7] (ii) 147 abrupt growth releases from the same trees, defined as a doubling (or greater) in the ring widths, by a step function, relative to the earlier sequence (for clarification see Figure 2).

[8] To obtain accurate germination dates, we took disk samples at the level of the soil litter layer from trees with diameters less than ~10 cm. From the few remaining larger trees, 5 mm increment cores were taken above ground at an angle so as to hit the sprout area or root collar. Disks and cores were polished [Stokes and Smiley, 1968] and micro cuts prepared, when rings were exceptionally narrow [Schweingruber, 1978]. These procedures, especially sampling at the level of the soil litter layer, minimize possible dating errors for determining the exact year of tree germination. We estimate a year error to be ≤ 3 years.

[9] Due to the large area considered in this study and the differing ecological situations found in the field (Table 1) a stringent ecological classification of all sites is impractical. We therefore classify the sites more generally into "Forest Boundaries", defined as the transitional zone from a closed forest to the open edges of the forest, and "Ecotones", defined as the transitional zone between the forest boundary and tundra environments, i.e., they represent saplings that advanced into the genuine treeless tundra in the 20th

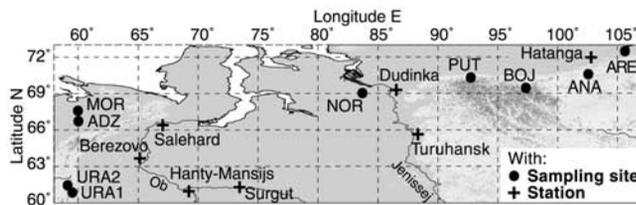


Figure 1. Map showing treeline sampling sites and climate stations. URA1 = N-Ural 1, URA2 = N-Ural 2, both *Pinus*; MOR = More Ju, ADZ = Adzva, both *Picea*; NOR = W Norilsk, PUT = Putorana, BOJ = Bojarska, ANA = Anabarskoe, ARE = Aremas, all *Larix*.

century. The latter are additionally sub-classified as “Elevation Ecotones”, when upslope of the upper forest boundary, and as “Wind Ecotones” for wind-stressed sites in the area of the northern forest boundary. Trees sampled are split into upright saplings <0.5 m and >0.5 m, and krummholz growth forms [Kullmann, 1981; Payette *et al.*, 1985].

[10] The sampled material represents a compilation of tree species, *Pinus sibirica* (Siberian pine) from the northern Urals, *Picea obovata* (spruce) from west of the Urals, *Larix sibirica* and *Larix cajanderi* (larch) from east of the Urals (Table 1). The sites MOR, ADZ, NOR are located in forest enclaves within the subarctic tundra, PUT and BOJ are in the Putorana Mountains, ARE is on the Taimyr Peninsula, ANA on the Anabarskoe Plateau, and URA-1 and URA-2 are in the northern Urals. All sites lie above permafrost, on gentle slopes, summits or plateaus, and are without impact from humans, fire, changing water tables, solifluction, and away from reindeer paths.

[11] The entire region is characterized by continental, dry climates with long and cold winters. There is, however, a longitudinal and a latitudinal structure across the network. Along the Ural Mountains, for example, the upper treeline declines from 1000 m a.s.l. at 61.0°N, to only 400 m a.s.l. at 66.5°N. And the average annual numbers of days with mean daily temperatures >10°C is 60 at Salehard (66.5°N/66.7°E, 24 m a.s.l.) vs. 26 at Hatanga (72.0°N/102.5°E, 50 m a.s.l.) about 50 km and 70 km south of the northern forest boundary, respectively [Walther and Lieth, 1960–1967] (see Figure 1). Within the network the period of cambial activity is short. We found that pine in the northern Urals and spruce west of the Urals had started latewood production by June 16, 2001, and ring growth in larch from the Putorana Mountains was already completed by August 01, 2001.

3. Treeline Changes

[12] Pulses of treeline changes are recorded in the mid and late 20th century (Figure 3). Even though these pulses seem to be synchronous between several of the sampling sites studied, significant regional-scale differences can be seen: The first recruitment wave 1940–1960 is found in seven of the nine sites (not in URA-2 and ARE). Trees that germinated during this period have upright growth forms except for the wind ecotones where they persist in micro-site depressions as krummholz (Figure 3c). A second period of enhanced recruitment started around 1972 east of the Urals (four sites) lasting into the 1980s (Figure 3a). Around

1983, in the northern Urals, upright trees <0.5 m started to establish and grow further upslope. Contemporaneously, rapid increases of radial tree growth over the entire transect are observed (Figure 3, crosses).

[13] Only a few older krummholz trees that germinated in the late 18th and 19th centuries were found within the network (Figure 3c). In general, at sites where trees have migrated into the treeless subarctic tundra they are all less than 75 years old independently of growth form.

[14] The majority of sampled trees grew extremely slowly after germination (Figure 2). A random sample of 44 differently aged trees indicates that such initial periods of restricted juvenile growth last between 3 and 22 years with mean (and min.-max.) growth rates of only 0.10 (0.04–0.15), 0.09 (0.06–0.16), and 0.07 (0.03–0.11) mm/year at URA-1, PUT, and ANA, respectively. At URA-1 79%, and at PUT and ANA 100% of samples showed this period of suppressed growth.

[15] No mortality data can be provided from these periods to document the loss of saplings. If saplings survive the initial restricted growth period they may reach heights of 4 m after about 50 years in favorable microclimatic situations (e.g., NOR), or remain as krummholz in wind ecotones (e.g., ADZ).

4. Correspondence With Climate

[16] Over this large area it is not possible to relate the observed treeline changes to detailed environmental forcing data at the local scale. First, there are few such data available from the study regions in western Siberia. Secondly, data from an individual site might only show a single recruitment or release period. Further, relating such data (i.e., the counting/dating of plants and growth events) with higher-order temperature data, for example, does not allow simple techniques to demonstrate the statistical significance of relationships, let alone to prove causality. With these limitations in mind, here we merge the data from the nine sampling sites to provide an overview of treeline changes, and graphically compare these findings with large-scale temperature patterns recorded at seven western Siberian meteorological stations (Figure 4).

[17] The recorded 20th century treeline changes correspond with annual decadal-scale temperature variations. This correspondence can be visually verified by comparing the germination dates of surviving saplings and abrupt



Figure 2. Cross section of a 64-year old *Larix sibirica* from the Anabarskoe plateau. The initial period of restricted growth, with a mean ring width of 0.035 mm/year, is interrupted by a wide ring (arrow). In 1989 (two arrows) an abrupt growth release, defined as a doubling (or greater) in ring widths over more than three years, occurred and ring widths increased to 0.2 mm/year. Scale bar is 1 mm.

Table 1. Sampling Site, Forest Type and Tree Type Characteristics^a

Site	Species	Lat./Lon.	Elevation	Exp./Inc.	Forest Type	Tree Type	Samples
N-Ural 1	<i>Pinus sibirica</i>	61°26'N/59°43'E	920–950 m	–/0°	Wind ecotone	Saplings and Krummholz	84
N-Ural 2	<i>Pinus sibirica</i>	61°49'N/59°22'E	730–800 m	S/10°	Wind ecotone	Saplings	23
More Ju	<i>Picea obovata</i>	67°49'N/60°01'E	25–50 m	S/5°	Forest boundary	Krummholz	36
Adzva	<i>Picea obovata</i>	67°08'N/60°00'E	60–90 m	S/15°	Wind ecot., Forest bound.	Krummholz and Trees	31
W Norilsk	<i>Larix species</i>	69°01'N/83°40'E	30 m	–/0°	Wind ecot., Forest bound.	Saplings and Trees	21
Putorana	<i>Larix species</i>	70°31'N/92°57'E	350 m	S/8°	Elevation ecotone	Saplings and Krummholz	17
Bojarska	<i>Larix species</i>	69°57'N/97°37'E	590 m	S/2°	Elevation ecotone	Saplings, Krummholz, Trees	38
Anabarskoe	<i>Larix species</i>	70°52'N/102°53'E	220 m	N/3°	Elevation ecotone	Saplings and Krummholz	20
Arema	<i>Larix species</i>	72°23'N/105°52'E	30 m	N/5°	Elevation ecotone	Saplings	6

^aExp./Inc. indicate exposition and inclination of sites. Some of the variance in the numbers of samples is related to logistical problems and field accessibility.

radial growth releases with mean annual temperature patterns (Figure 4). The germination and growth releases in the 1940s–1950s and after the early 1970s correspond with decades of annual temperatures that are warmer than in any other period since observations started. The significance of temperature-forced treeline dynamics in western Siberia is additionally supported by the highly synchronous variations of temperature recorded at the seven meteorological stations (Figure 4, thin lines).

[18] For western Siberia, the correspondence with growing season (JJA) temperature variation is lower (Figure 4 (top)) than with annual temperature variation, suggesting that summer conditions alone would not as well explain the observed germination and growth releases. JJA temperatures show a delayed warming peak during the middle of the 20th century in the 1950s. Additionally, a warming trend in recent decades, as recorded in annual temperatures, is broadly missing. This well-documented [Hansen *et al.*, 1999; Jones *et al.*, 1999], significant trend in Siberia is predominantly driven by winter temperatures.

[19] The lack of germination events prior to the mid 20th century indicates this is an exceptional advance, the relict stumps and logs found at all sites, except URA-2, MOR and ADZ (Figure 3), show that this advance is part of a long-term reforestation process of tundra environments. While the decomposition rate of *Pinus sibirica* and *Picea obovata* remnants in the cold and dry Siberian climate is unknown, stumps and logs of *Larix sibirica* can be preserved for hundreds of years [Shiyatov, 1992]. Above the treeline in the Polar Urals such relict material from large, upright trees were sampled and dated, confirming the existence, around AD 1000, of a forest treeline 30 m above the late 20th

century limit [Shiyatov, 2003]. This previous forest limit receded around 1350, perhaps caused by a general cooling trend [Briffa, 2000; Esper *et al.*, 2002].

5. Discussion

[20] A mid 20th century recruitment period, synchronous with the advance shown from the western Siberian network, is reported from central Sweden (1946–55) [Kullmann, 1981], northern Finland (1945–47) [Kallio, 1975], northern Quebec (1938–63) [Morin and Payette, 1984], and the Polar Urals (1940–55) [Shiyatov, 1992]. Together with the current results these findings from Europe and North America support a circumpolar trend, likely related to a global climate, warming pattern [Hansen *et al.*, 1999; Jones *et al.*, 1999]. Except for eastern larch in northern Quebec, we are, however, not sure we can compare our results with others as we are not fully knowledgeable of the sampling strategy used in these previous studies. If the age determinations of these other studies did not include sampling above the root collar, differences between our timing and the timing proposed by others could be significant.

[21] In western Siberia, saplings germinated during the mid (and late) 20th century, survived the first two decades and developed after some 50 years forests with trees up to 4 m tall - at least in wind-protected sites. During the initial period of restricted growth exceptional winter frosts, together with little snow-cover-protection, may have stressed the saplings of all species. Also fungal diseases such as caused by *Phacidium infestans* have affected *Pinus sibirica* saplings (URA-1). In general, we assume that locally differing ice melting processes, at the level of the root

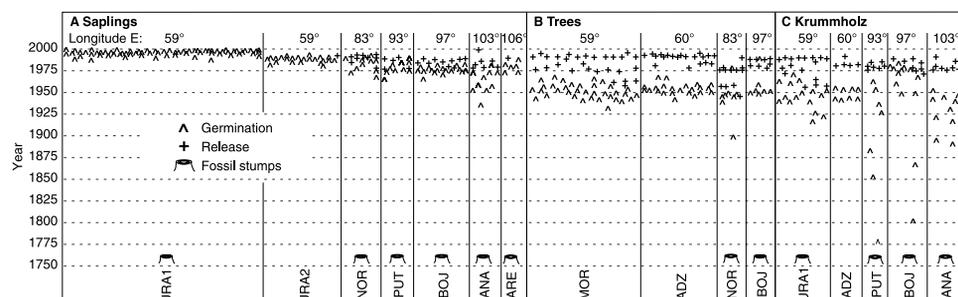


Figure 3. 276 germination dates and 147 growth release dates recorded in nine western Siberian sites. Tree growth forms and heights ordered: a, upright saplings <0.5 m, observed in seven sites; b, upright trees >0.5 m, observed in four sites; c, krummholz, observed in five sites. Fossil stumps and logs observed in URA-1, NOR, BOJ, PUT, ARE, ANA. For site locations and names see Figure 1.

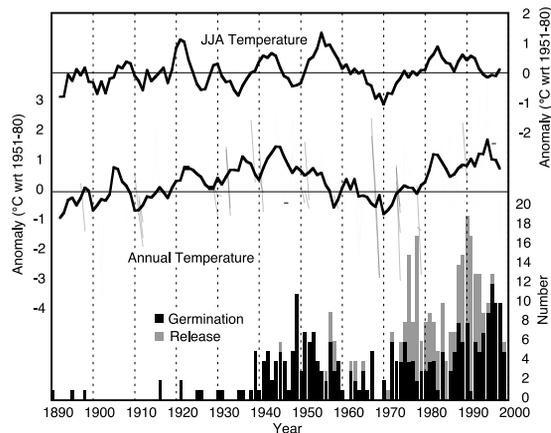


Figure 4. Mean JJA and annual temperature anomalies and the timing of tree germination and growth release. Thin lines indicate seven annual temperature records shown as anomalies from the 1951–1980 mean (climate stations and tree sites shown in Figure 1). Two stations (Berezovo, Turuhansk) have data back to 1881. The Syktyvkar station, west of the study area ($61^{\circ}70'N$, $50^{\circ}80'E$), has data back to 1817. No Siberian station indicates temperatures as warm as in the 20th century. Bold lines are 5-year running means. The histogram indicates numbers of tree germination and growth release recorded in nine western Siberian treeline sampling sites.

horizon above the permafrost [Karlsson and Nordell, 1996] are crucial for the survival rate of the saplings. Some of these processes seem to be controlled by surface temperatures [Turner and Streule, 1983] and might explain the correspondence with decadal-frequency, annual temperature variations.

[22] However, we do not have a specific ecological explanation for the temperature-driven abrupt growth releases contemporaneously recorded in the western Siberian network. A clear relationship between growth release and enhanced vertical growth, i.e., the change from prostrate to erect growth, as reported from northern Quebec [Payette *et al.*, 1985], cannot fully be confirmed for the western Siberian network, because these releases are present in both krummholz and upright (and skirted) [after Payette *et al.*, 1985] trees.

[23] The increased correspondence with annual mean temperatures rather than with summer temperatures, particularly towards the most recent decade, indicates both winter and summer conditions might be relevant for the invasion of trees into genuine treeless tundra environments. However, the nature of our treeline data and the generally sparse data availability for Siberia do not allow robust statistical analyses to be performed. Thus, the current results should not be over interpreted in terms of the specific ecological processes driving treeline changes, but are noteworthy because they indicate for the first time some large-scale dynamics in an area from which a significant Northern Hemisphere warming trend is reported [Hansen *et al.*, 1999; Jones *et al.*, 1999].

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