Landsat-based analysis of Mountain forest-tundra ecotone response to climate trends in Sayan Mountains, Siberia

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According to observations of temperatures Siberia has shown a several degree warming over the past 30 years. It is expected that forest will respond to warming at high latitudes through increased tree growth and northward or upward slope migration. migration. Tree response to climate trends is most likely observable in the forest-tundra ecotone, where temperature mainly limits tree growth. Making repeated satellite observations over several decades provides an opportunity to track vegetation response to climate change. Based on Landsat data of the Sayan Mountains, Siberia, there was an increase in forest stand crown closure and an upward tree-line shift in the of the forest-tundra ecotone during the last quarter of the 20th century,. On-ground observations, supporting these results, also showed regeneration of Siberian pine in the alpine tundra, and the transformation of prostrate Siberian pine and fir into arboreal (upright) forms. During this time period sparse stands transformed into closed stands, with existing closed stands increasing in area at a rate of ~ 1%/yr, and advancing their upper border at a vertical rate of ~ 1.0 m/yr. In addition, the vertical rate of regeneration propagation is ~5m/yr. It was also found that these changes correlated positively with temperature trends.

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Abstract

Models of climate change predict shifts of vegetation zones. Tree response to climate trends is most likely observable in the forest-tundra ecotone, where temperature mainly limits tree growth. Temporal satellite observations provide an opportunity to track vegetation response to climate change. Based on Landsat data of the Sayan Mountains, Siberia, there was an increase in forest stand crown closure and an upward tree-line shift in the of the forest-tundra ecotone during the last quarter of the 20th century,. On-ground observations, supporting these results, also showed regeneration of Siberian pine in the alpine tundra, and the transformation of prostrate Siberian pine and fir into arboreal (upright) forms. During this time period sparse stands transformed into closed stands, with existing closed stands increasing in area at a rate of ~ 1%/yr, and advancing their upper border at a vertical rate of ~ 1.0 m/yr. In addition, the vertical rate of regeneration propagation is ~5m/yr. It was also found that these changes correlated positively with temperature trends.

Satellite temporal data, climate trends, forest-tundra ecotone

Introduction

The global average temperature has increased ~ 0.6 K over the last century, with the most significant changes occurring in Siberia. Rapid further temperature increase in the next decades is predicted (Zwiers, 2002). After 1976, the trend of warming was approximately three times higher than for the previous century. Since 1987, the ten warmest years have been observed since the beginning of meteorological measurements (WMO 2002). The majority of researchers have accepted that climate change will entail change of extent and productivity of plants species and changes both in species, and at the ecosystem level are expected (Kappelle et al. 1999; Shaver et al. 2000; Saxe et al. 2001; Walther, 2003). There is now evidence of tree species invasion into the tundra, increases of a stand densities and radial increments along the northern tree line during the last decades of the 20th century, and "dark needle conifer " invasion into areas of larch dominance (Suarez et al, 1999; Payette et al, 2001; Lloyd, Fastie, 2002; Shiyatov, 2003; Kharuk et al., 2005). At the upper limit of tree growth data are more controversial. It was reported in several publications an upward shift of the upper tree border (Kullmann, 2002; Shiyatov, 2003). Whereas other investigations stated the stability of tree border during last decades (e.g., Klasner and Fagre 2002). Satellite data are now becoming an important tool for the climate-driven changes in vegetation, especially since several decades of satellite observations coincide with the most pronounced climate changes. Satellite temporal data analysis of Siberian northern tree line showed an increase of crown closure and tree propagation into tundra area (Kharuk et al., 2004). However, a similar Landsat-based study for Canadian forest-tundra zone did not find significant changes of the tree border (Masek, 2001).

The mountain forest-tundra ecotone is similar to the northern forest-tundra ecotone: in both cases temperature controls tree growth. As temperature increases, vegetation is likely to respond with increasing canopy closure, and regeneration at higher altitudes. Mountain ecotones differ from northern ones by the stronger temperature gradient; consequently, vegetation changes along this gradient occur at the scale of 10-100 meters, whereas in the northern ecotone similar changes are expected at the scale of kilometers. In addition, mountain areas are also characterized by mostly clear atmosphere. Thus, as an object of investigation, the mountain ecotone is excellent for satellite data application.

The purpose of this investigation was to analyze mountain forest-tundra ecotone dynamics based on a temporal series of Landsat observations. Since mountain landscape features have a strong impact on vegetation patterns, our second purpose was to analyze vegetation dynamics with respect to topography.

Material and methods

Study site

The investigated area is located in the Western Sayan Mountains in central Siberia (Fig. 1). It is a complex of ridges dissected by a widespread drainage network. Topgraphically the territory is very heterogeneous and therefore climatic conditions and ecosystems are very diverse. The forest or taiga landscapes cover most parts of north facing slopes and the tops of south facing slopes. The elevation varies from 2400 m above sea level to 1300-1500 m in the basins. Specifically, elevation varies for north facing slopes from 800-900 m to 1500-1800 m. These slopes are covered by dark needle coniferous forest with predominance of Siberian pine (*Pinus sibirica*), fir (*Abies sibirica*) and spruce (*Picea obovata*). Forest types are arranged in altitudinal belts including pine-birch forest-steppe (up to 250-300 m), the narrow belt of light coniferous and mixed stands (up to 400-450 m) and dark needle coniferous stands (up to 1600-1700 m) which gradually transform to a sub-alpine belt of meadows and sparse fir-Siberian pine stands (1600-1800 m). At the upper treeline the forest gradually degrades and transforms to sparse Siberian pine (on northern facing slopes) and larch (on southern facing slope). At higher elevations there are very sparse stands mixed with mountain tundra, bushes, alpine meadows and stony areas. The climate is severe continental: in mountains a mean January temperatures are -28 to -34°C, and in July 10-12°C. Maximum precipitation falls during the summer. The quantity of precipitations mostly depends on altitude and orientation of slopes and ranges from 400-500 mm/yr (in the northern foothills) up to 1000-1500 mm/yr (on the northern windward slopes); in the southern slopes amount the amount of precipitation is 400-500 mm/yr. The study site included mostly the upper windward slopes (fig. 1). The analyzed area covers about 60,000 ha.

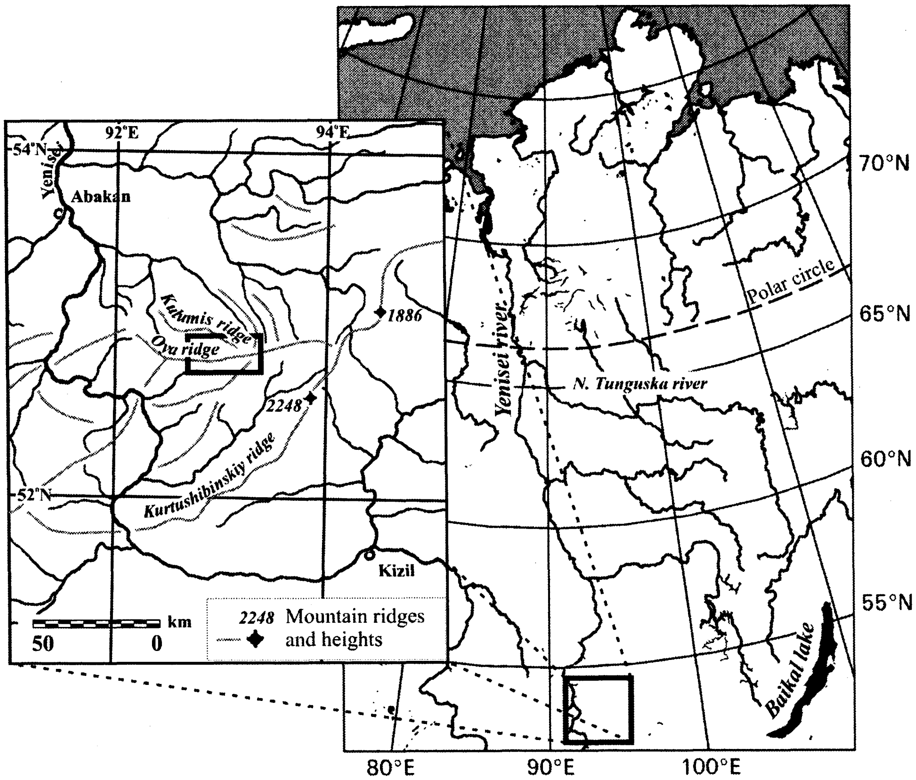

Fig. 1. The area of investigation was the Sayan Mountains in south-central Siberia. Box on the insert indicates location of Landsat image data.

Satellite data

Landsat-MSS (acquired 05 September 1976) and Landsat -7 (acquired 10 September 2000) were used in the analysis. Landsat has been used effectively for a number forest change studies (e.g., Kharuk et al, 2006). The satellite image data were processed by Erdas Imagine software package [http://gi.leica-geosystems.com/]. Statistica (Statsoft 2003) and Microsoft Excel were used to for statistical calculations. Classification accuracy was estimated by KHAT(κ)-statistics method ([Lillesand and Kiefer, 1994). Landsat scenes were imported to ERDAS Imagine environment and converted to the UTM projection, WGS84, zone 46. To facilitate comparisons of data from the two satellites, Landsat-7 pixel size (30x30m) was resampled to 60 × 60 m to conform to Landsat MSS. Landsat-MSS data were then georeferenced to the Landsat-7 scene (validated geodesic accuracy of the latter is 30 m). An atmospheric correction was not used since the analyzed area is located at high elevation with typically clear atmosphere.

The C-factor method for topographic normalization (Meyer et al., 1993; Riaño et al., 2003) was applied to reduce topographic effects which are essential in mountains and accounts for variations in solar illumination as a function of the projected slope angle. A digital elevation model (DEM) was used in C-factor calculations and to exclude areas below 1300 m in elevation which are definitely below the forest-tundra ecotone. The Shuttle Radar Topographic Mission (SRTM) DEM was used with spatial resolution 90 m and nominal vertical accuracy of ±15 m (USGS 2007) .

Supervised classification was applied for image analysis; Class spectral statistics were examined and found to be normally distributed. Classification depended on ground truth data for representative areas of known classes (the number of test areas used was 41) and forest inventory maps (dated 1976 and 2000 , with map scales of 1:50,000 to 1:100,000).

Training area data for Landsat-2 MSS and Landsat-7 ETM+ scenes are presented in Tables 1 and 2, correspondingly. Since the tree line is actually a transition from forest stands to treeless tundra we examined the border of the stands with crown closure (CC) exceeding 0.3 (i.e., CC>0.3). This definition also corresponds to the conventional closed stands definition. In the Landsat image analyses six ground cover classes were identified: closed stands (crown closure (CC)> 0.3: CC03), sparse stands (CC < 0.3: CC00), Siberian pine prostrate forms and regeneration (PR), grass and shrub communities (GRS), mineralized surfaces (STN), and water bodies (WTR).

To adequately characterize the land cover change from the years 1976 and 2000 we used a set of decision rules based on ground observations and current maps for 1976 and 2000, (Table 3). The decision rules were based on the following logic.

If a pixel was classified as regeneration (PR) in the 1976 image and classified as PR, CC00 CC03 or GRS in the 2000 image, the resulting class was marked PR. This logic is based on the fact that the spectral characteristics of regeneration and sparse stands are very similar; and in the case of dense regeneration these classes could be not be differentiated . On the other hand, the 25 year period of observation is not long enough for regeneration to convert into forest stands. In the case of sparse regeneration this class is known to be mixed with grasses. Our on-ground studies shown that during the period of observation the regeneration density increased (e.g., Fig 2).

Table 1. Training area data for Landsat-MSS

No	Class	Total pixels	Total samples	Mean brightness / standard deviation for spectral bands				Classifier error, %
				4	5	6	7	
1	PR	17	3	39.9/7.7	51.7/13.0	93.2/4.7	98.8/3.8	3.2
2	CC00	123	10	28.4/2.1	30.7/3.5	73.5/3.5	76.6/4.1	2.2
3	CC03	4249	25	23.8/1.6	18.4/2.2	66.6/1.6	67.9/1.7	0.7
4	GRS	141	11	41.0/18.0	49.0/18.7	88.4/9.8	92.3/8.3	4.9
5	STN	107	6	56.6/10.0	56.9/7.7	75.1/2.0	72.0/1.7	0.3
6	WTR	96	1	19.5/1.7	10.8/1.1	51.8/0.7	51.1/0.3	0.0

CC03 - closed stands (CC > 0.3), CC00 - sparse stands (CC < 0.3), PR - Siberian pine prostrate forms and regeneration, GRS - grass and shrub communities, STN– bare mineral surfaces, WTR - water bodies.

Table 2. Training area data for Landsat-7

No	Class	Total pixels	Total samples	Mean brightness/ standard deviation for spectral bands*						Classifier error, %
				1	2	3	4	5	7	
1	PR	1543	2	118.8/ 4.9	101.9/ 5.1	96.8/ 6.1	108.4/ 7.7	110.2/ 7.5	85.6/ 6.4	6.4
2	CC00	98	8	115.3/ 4.5	97.6/ 6.0	88.3/ 9.2	97.2/ 9.2	93.7/ 12.6	75.3/ 11.3	5.8
3	CC03	7585	30	108.9/ 3.5	81.9/ 3.4	60.0/ 4.3	62.3/ 4.6	44.1/ 4.6	38.6/ 4.5	0.1
4	GRS	749	15	129.3/ 5.8	120.8/ 7.0	119.9/ 11.9	115.4/ 12.7	127.3/ 13.3	106.0/ 15.0	2.9
5	STN	230	6	175.2/ 19.9	162.2/ 22.9	155.1/ 20.6	80.8/ 11.8	118.5/ 4.2	140.3/ 15.3	0.7
6	WTR	403	1	106.4/ 3.1	69.5/ 2.7	48.4/ 3.0	18.9/ 1.7	14.4/ 1.6	18.9/ 2.6	0.0

For definitions of abbreviations see Table 1

If a pixel classified as CC00 in 1976 was classified as PR in 2000, it was labeled CC00 in 2000 (again because of similar spectral characteristics). Note that study area is within a forest preserve, i.e. there were no clear cuts.

If CC00 (1976) was classified as GR (2000) then those pixels were classified as GRS. A similar logic was used for bare stony surfaces (STN).

The class CC00 includes sparse stands with crown closure< 0.3, in some cases the grass and shrub class was confused this class. To be conservative, we marked those classes GRS; i.e. decreasing commission error. A similar logic for the STN (bare rock surfaces) was used here as well.

If CC03 (1976) were classified as regeneration (PR), then the class remained as CC03, because of similar spectral characteristics. In the case of GRS and STN the logic is similar as for CC0: to be conservative, and decrease commission error.

Results

Landsat-derived forest-tundra ecotone dynamics

The Landsat-MSS (1976) and Landsat-7 (2000) derived maps are presented as fig. 2. They show that during a quarter of century considerable changes of the land cover classes have occurred. The producer accuracy for Landsat-MSS derived classification is minimal for the PR class -regeneration and tree prostrate forms (76%), whereas user accuracy and kappa-statistics have minimal values for class GRS -grasses" (Table 4). For the Landsat-7 derived map minimal accuracy (61 - 65 %) was observed for sparse stands (Table 5). Overall accuracy in both cases are high (total accuracy >90%, total kappa ≥0.85). The class transformations ("origin" and "destination" of ground cover classes) for the period between L-3-MSS data (1976) and L-7 (2000) are shown in the "transition matrix" (Table 6).

Table 3. The decision rules

	IF		THEN	
	"Old" classes		"New" classes	
	1976	2000	1976	2000
1	PR	CC00	PR	PR
2		CC03		
3		GRS		
4	CC00	PR	CC00	CC00
5		GRS	GRS	GRS
6		STN	STN	STN
7	CC03	PR STL	CC03	CC03
8		CC00		
9		GRS	GRS	GRS
10		STN	STN	STN
11	GRS	CC00	GRS	PR
12		CC03	GRS	CC00
13		STN	STN	STN
14	STN	CC00	STN	PR
15		CC03		

Abbreviations: see table 1

Table 4. Classification accuracy of Landsat –3 MSS derived map (1976)

Class number								T_{ref}	T_{cls}	T_{cor}	$A_{cls.}$, %	A_{usr}, %	E_o, %	E_c, %	κ
		PR	CC00	CC03	GRS	STN	WTR								
1	PR	29	0	0	2	0	0	38	31	29	3	93.5	23.7	6.5	0.93
2	CC00	0	25	11	0	0	0	32	36	25	78.1	69.4	21.9	30.6	0.66
3	CC03	0	1	184	0	0	0	200	185	184	92	99.5	8	0.5	0.99
4	GRS	9	5	5	39	0	0	42	58	39	92.9	67.2	7.1	32.8	0.63
5	STN	0	1	0	1	35	0	35	37	35	100	94.5	0	5.4	0.94
6	WTR	0	0	0	0	0	10	10	10	10	100	100	0	0	1
Total accuracy = 90.2%															
Total kappa = 0.85															

PR – regeneration and tree prostrate forms, CC00 – sparse stands, CC03 – closed stands, GRS – grass and bush communities, STN – mineralized surfaces, WTR – water bodies. T_{ref} – total number of referenced points; T_{cls} – total number of estimated points; T_{cor} – total number of correctly identified points; A_{cls} – producer accuracy; A_{usr} – user accuracy; E_o – omission error; E_c – commission error; κ – kappa-statistics value.

Table 5. Classification accuracy of Landsat – 7 derived map (2000)

Class number								T_{ref}	T_{cls}	T_{cor}	A_{cls}, %	A_{usr}, %	E_o, %	E_c, %	κ
		PR	CC00	CC03	GRS	STN	WTR								
1	PR	32	4	0	2	0	0	36	38	32	88.9	84.21	11.11	15.79	0.82
2	CC00	0	13	7	0	0	0	21	20	13	61.9	65	38.1	35	0.63
3	CC03	0	0	193	0	0	0	200	193	193	96.5	100	3.5	0	1
4	GRS	4	4	0	25	0	0	28	33	25	89.3	75.8	10.7	24.2	0.74
5	STN	0	0	0	1	35	0	35	36	35	100	97.2	0	2.8	0.97
6	WTR	0	0	0	0	0	10	10	10	10	100	100	0	0	1
Total accuracy = 93.3%															
Total kappa = 0.89															

Abbreviations: see Table 5.

Table 6. Ground cover transition matrix (Landsat-7 minus Landsat-MSS derived maps).

Landsat-7 derived classes	Landsat-MSS derived classes, % of Landsat-7 derived classes				
	PR	CC00	CC03	GRS	STN
PR	36.4	0.0	0.0	59.8	3.8
CC00	0.0	91.1	0.0	8.9	0.0
CC03	0.0	15.9	84.1	0.0	0.0
GRS	0.0	0.0	0.0	96.3	3.7
STN	0.0	0.0	0.0	0.0	100.0

Abbreviations: see Table 5.

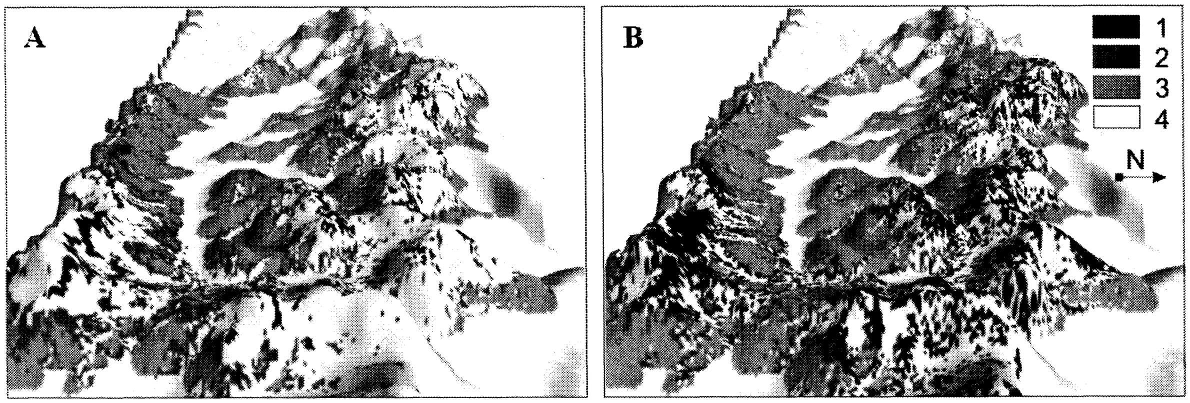

Fig. 2. Landsat-derived 3D view on the vegetation classes in 1976 (left) and 2000 (right). 1 – Siberian pine regeneration and prostrate forms, 2 – sparse stands (CC< 0.3), 3 – closed stands (CC>0.3); 4 – grass and bush communities, 5 – mineralized surfaces; 6 - water bodies.

Table 7. Ground cover classes dynamics for the period of 1976 -2000 yrs

	Class	Δ, ha	Δ, %	Δ_{yr}, %
1	PR	2509	174.9	7.6
2	CC00	-2003	-40.6	-1.8
3	CC03	2264	18.9	0.8
4	GRS	-2423	-31.1	-1.4

Δ - area difference between ground cover classes on Landsat—7 derived map (2000) and Landsat-MSS derived map (1976);

Δ_{yr} – annual ground cover class difference.

Other abbreviations: see Table 5.

Relationship between forest-tundra ecotone dynamics and topography

Landscape plays an important role for trees survival under harsh climatic conditions. To relate changes in forest-tundra with topography, the SRTM DEM was used (http://srtm.usgs.gov/). Slope and aspect were calculated and put into rasterized data layers in a GIS. These data were then normalized, i.e., referenced as the proportion for a given slope, aspect or altitude to the whole analyzed area.

Data shown as Fig. 3 indicates that Siberian pine regeneration propagates irrespective of aspect (with slight preference for north and south-east facing slopes). Closed stands increased in area evenly at all aspects.

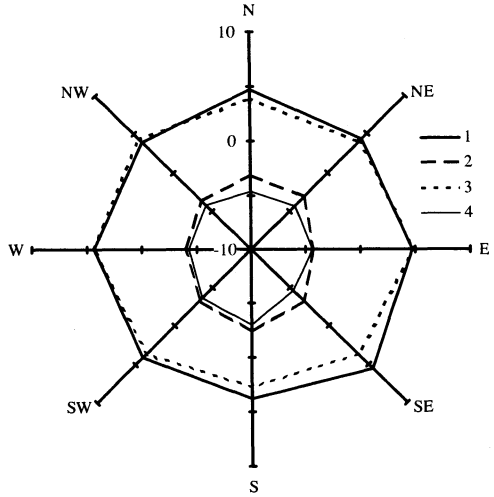

Figure 3. Landscape aspect distribution illustrating land cover classes dynamics (in percent area) during the period 1976 to 2000.

1 – Siberian pine regeneration and prostrate forms, 2 – sparse stands (CC< 0.3), 3 - closed stands (CC>0.3); 4 – grass and bush communities.

With respect to steepness, during the last decades the regeneration actively started occupation of steep (>25 deg) slopes (fig. 4). Before the warming these areas were less suitable for forest growth.

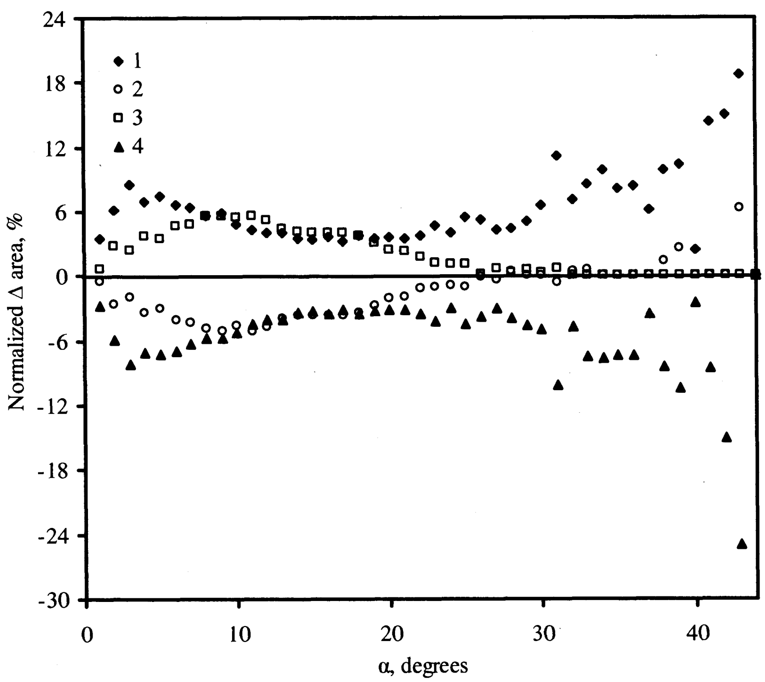

Figure 4. Landscape slope steepness distribution illustrating land cover classes dynamics (in percent area) during the period 1976 to 2000.

1 – Siberian pine regeneration and prostrate forms, 2 – sparse stands (CC< 0.3), 3 – closed stands (CC>0.3); 4 – grass and bush communities.

The diagram on Fig. 5 shows transformation of the ground classes during the period 1976 to 2000 yr. Sparse stands transforms mainly into closed stands, and grass and bush communities – into regeneration.

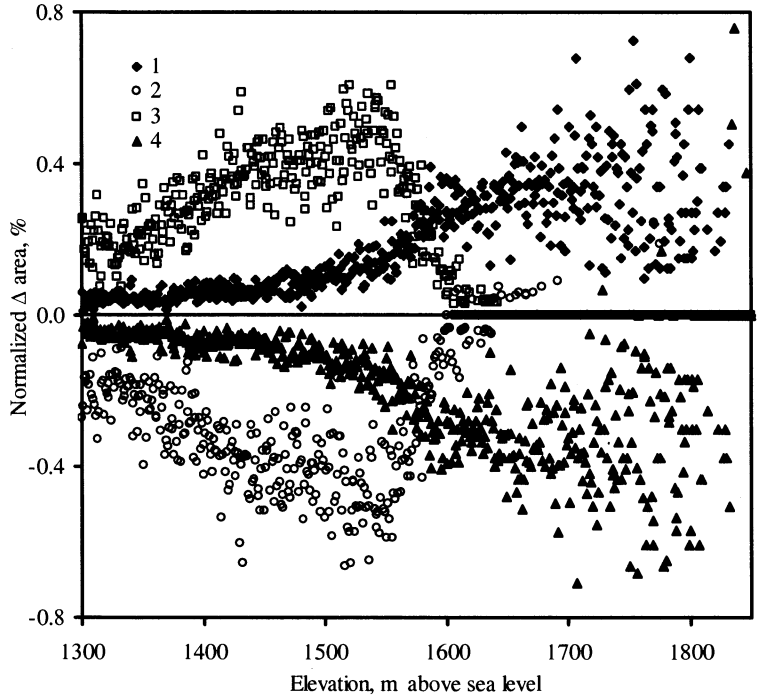

Figure 5. Landscape altitude distribution illustrating land cover classes dynamics (in percent area) during the period 1976 to 2000.

1 – Siberian pine regeneration and prostrate forms, 2 – sparse stands (CC< 0.3), 3 - closed stands (CC>0.3); 4 – grass and bush communities.

Vegetation propagation rate

Two rates of vegetation propagation were estimated: the “planar” (or projection on the horizontal plane), and the “vertical” (or projection on vertical axis) rate. For stands the planar rate was estimated using generated maps: maps, corresponding the years 2000 and 1976 were overlapped, and the difference between borders (in 2000 and 1976) was calculated base on scanning. The vertical rate was evaluated by adding the information from DEM. The mean “planar” rate of closed stands was found to be ~4.5 m/yr, and the mean vertical rate ~1.0 m/yr. The propagation rate of sparse stands was within the error. The similar approach was used for Siberian pine regeneration propagation rate. The regeneration (and prostrate forms) boundary which corresponded to year 1976 was delineated based on the regeneration age structure; the last was determined based on on-ground studies. The planar rate of regeneration propagation was estimated as ~10 m/yr, and vertical rate as ~5m/yr. It was found that during period of 1976-2000 yr. regeneration reached the highest investigated mountain tops; since that, the maximal rate should be even higher.

Discussion

Landsat-based quarter-century temporal analysis in the Sayan Mountains forest-tundra ecotone showed significant changes in the main vegetation classes. During this time period sparse stands transformed into closed stands, with existing closed stands increasing in area at a rate of ~ 1 %/yr, and advancing their upper border by ~ 1.0 m/yr, and regeneration was propagating into tundra with vertical rate about 5m/yr. On-ground observations showed that during last decades Siberian pine intensively occupied areas which before were covered by shrubs and grasses. In addition, a transformation of prostrate Siberian pine and fir into arboreal forms was observed.

The increase of canopy closure found by Landsat-data analysis was supported by in situ measurements of apical increment and in-lab analysis of tree radial increment. (Kharuk at al 2006). Within alpine tree border tree growth is controlled by summer temperatures and the mean of these temperatures increased by ~1C° between the Landsat -MSS and Landsat -7 acquisitions. The other important vegetation response to increased temperatures, the propagation of regeneration into the tundra zone is a slower process since establishment of new generations of trees follows the climatic changes with a lag caused by germination capacity, seeds dispersal, and seedlings survival. That's why an actual tree-line is not corresponding to its potential position, since during the warming period the tree line is behind its potential climatic border, and *vice verse* during periods of cooling . For Siberian pine this lag is minimal and we observed a quick propagation of Siberian pine saplings and seedlings into the tundra . This process is promoted by a bird and mammals species, which disseminates seeds to radius of 1-2 km from "mother stands". Thus, the "breeding potential", which limits tree species propagation in the forest-tundra ecotone (for example, larch propagation of Polar Urals Mountains: Shiyatov, 2003), is not a case for a Siberian pine in Sayan Mountains.

Described observations are a part of the broader phenomena of Siberian taiga species response to climate change. Earlier it was shown that during last decades Siberian pine, spruce and fir are appearing within areas previously dominated by larch.. On the western and southern margins of larch dominance these species are forming a second layer in the forest canopies, which could eventually replace the larch in the overstory (Kharuk et al, 2005). Larch, in its turn, as shown by satellite-based analysis and on-ground data, is propagating into northern tundra zone (Kharuk et al, 2004). Continental scale of observing phenomena needs further analysis of temporal rows of remotely obtained.

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