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Epigenetic salt accumulation and water movement in the active layer of central Yakutia in eastern Siberia

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Abstract:

Observations of soil moisture and salt content were conducted from May to August at Neleger station in eastern Siberia. Seasonal changes of salt and soil moisture distribution in the active layer of larch forest (undisturbed) and a thermokarst depression known as an alas (disturbed) were studied. Electric conductivity EC_e of the intact forest revealed higher concentrations that increased with depth from the soil surface into the active layer and the underlying permafrost: 1 mS cm^{-1} at 1·1 m, to 2·6 mS cm^{-1} at 160 cm depth in the permafrost. However, a maximum value of 5·4 mS cm^{-1} at 0·6 m depth was found in the dry area of the alas. The concentration of ions, especially Na^+, Mg^{2+}, Ca^{2+}, SO_4^{2-} and HCO_3^- in the upper layers of this long-term disturbed site, indicates the upward movement of ions together with water. A higher concentration of solutes was found in profiles with deeper seasonal thawing. The accumulation of salts in the alas occurs from spring through into the growing season. The low concentration of salt in the surface soil layers appears to be linked to leaching of salts by rainfall. There are substantial differences between water content and electric conductivity of soil in the forest and alas. Modern salinization of the active layer in the alas is epigenetic, and it happens in summer as a result of spring water collection and high summer evaporation; the gradual salt accumulation in the alas in comparison with the forest is controlled by the annual balance of water and salts in the active layer. Present climatic trends point to continuous permafrost degradation in eastern Siberia increasing the risk of surface salinization, which has already contributed to changing the landscape by hindering the growth of forest. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS active layer; salt accumulation; seasonal thawing; soil moisture; permafrost

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INTRODUCTION

Saline soils are one of the major environmental problems in arid areas, where there is insufficient rainfall to leach salts from the root zone (Qadir *et al*., 2001), but they have been poorly studied in northern areas (Desyatkin, 1993). In eastern Siberia, 'continental' salinization is caused by a predominance of evaporation over precipitation, as well as by the annual and long-term freezing and thawing of soil, and is characterized by a prevalence of carbonate and sulphate ions (Anisimova and Kurchatova, 2000). Saline soils freeze at lower temperatures, contain more unfrozen water and have lower thermal conductivity in the frozen state. The increase in salt content can lead to an increase in active-layer depth and the formation of a thaw unconformity (Pewe and Sellmann, 1973). Active-layer salt content may also indicate the impact of climate warming and active-layer deepening (Wolfe *et al*., 2000). There is an area of about 44×10^4 ha of thermokarst depressions represented by grassland and called 'alases' in eastern Siberia, which were apparently formed by subsidence resulting from thawing of the upper part of the permafrost after a strong disturbance that occurred a few tens of thousand of years ago (Fitzpatrick, 1983). In central Yakutia alone there are about 16 000 alases (Bosikov, 1991). Modern disturbances and recent climatic changes continue to cause active-layer deepening and activation of young thermokarst depressions by the thawing of upper ground ice on stable areas of inter-alas meadows (Fedorov and Konstantinov, 2003). The regime of flooding and desiccation of alas depressions and metamorphic evolution of alas soils is linked to further cyclic variations in climate and soil development, which can contribute to redistribution and accumulation of salts. The general effect of salinity is to reduce the growth rate of vegetation or prevent growth entirely, depending on the salt sensitivity of the vegetation (Shannon and Grieve, 1999). After disturbance, former forest stands are replaced by vegetation with different water demands, root systems and, in consequence, a different water balance. It is essential to understand the mechanisms involved in the establishment of these ecosystems; this is especially the case in relation to the redistribution of salts in the active layer in summer, since this is their most important characteristic. The aims of this study are to assess salt accumulation in the active layer of long-disturbed areas relative to intact forest, and to investigate

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the seasonal movement of water and salts in the active layer.

MATERIAL AND METHODS

Study site

Neleger Experimental Station is located 30 km north-northwest of the city of Yakutsk (62°05′N, 129°45′E) and belongs to the Permafrost Institute. Mean annual air temperature is −10 to −11 °C; the amplitude of monthly temperatures is about 62 °C. Snow cover is 30–40 cm, but can reach 60 cm. Typical permafrost temperatures are −2·0 °C (alas) to −3·5 °C (forest) at depths of 15–20 m. Icy deposits are located at depths from 1·5 m to about 3 m; they occur over more than half of the territory and have thicknesses of up to 20–25 m. The area consists of a group of Lena River terraces with elevations of 200–220 m a.s.l.; it is a region of continuous permafrost up to 400–500 m thick. Quaternary deposits are from a few metres to 200 m in thickness. The bedrock consists predominantly of limestones and argillites. Disturbances that occurred around 9000 years ago, which still continue, have changed the landscape of this area to birch forests or grassland (alas). Precipitation during the snow-free growing season is 110 mm, which is about half the annual precipitation, whereas the corresponding potential evaporation rate is 370 mm (Muller, 1982). Soils in this region are classified as Gelisols; they are silty-clay-loam (SiCL) to silty-clay (SiC). The mean grain diameter ranges from 0·016 to 0·039 mm; particles from 0·009 to 0·024 mm settle out in the central part of the alas and 0·054 mm particles in the marginal parts. Samples were collected at five locations of a forest–alas transect, with a depression from the forest to the alas of approximately 3 m, and consisted of dominant vegetation at each location as follows: *Larix cajanderi* (in the forest, F-site), *Betula platyphylla* (in the slope, S-site), *Elytrigia repens* (in the alas border, AB-site) *Carex vesicata* (in the middle of the alas, AM-site) and *Elytrygia repens* (in the pingo, P-site). The pingo, a small hill (almost 3 m high) at the edge of the alas lake in the thermokarst, formed by the land freezing (Figure 1). Between the forest and alas there is commonly a belt of birch trees, which is referred to in this study as the S-site because of the slope where it is located.

As in most saline soils, salt concentration shows spatial differences, and at several points in the alas it will depend in factors such as salt content in the former permafrost and in the topographical changes after subsidence. The active layer of grasslands in the Lena River valley region is salted as a result of similar geological and climatic conditions.

Sampling

Two soil samples were collected approximately every 2 weeks at each location, starting in May 2004. The first sampling occurred when the soil profile was still frozen from the surface to 160 cm and required a boring machine. After soil thawing started, cores were extracted as the soil thawed using a 5 cm diameter core barrel. The frozen layer was estimated by an increase in ground resistance to drilling and an appearance of visible ground-ice content. The core samples were sectioned in 10 cm intervals, logged, double-bagged and returned to a laboratory.

Figure 1. IKONOS image of Neleger showing the sites considered for sampling in this study (July 2002, provided by Japan Space Imaging Corporation)

Soil moisture and chemical analysis

Soil moisture of the thawing soil layer was determined gravimetrically by drying to a constant weight at 105 °C for 24 h. Soil water potential was measured in June and July in the F- and AB-sites from the surface to the maximum soil depth (water potential meter, WP4). Soil samples were air dried for more than 2 weeks. From every 10 cm within the soil profile, 5 g of soil was transferred into a bottle and mixed with 25 ml of deionized water and shaken in a mechanical shaker for 1 h to attain a supernatant suspension of 1 : 5 soil : deionized water mixture (Page *et al.*, 1982). Electric conductivity (EC meter TOA CM-30V) and pH (pH meter Horiba) were measured for all soil profiles from each sampling site. Electric conductivity of saturated paste EC_e, used to evaluate saline and alkaline soils, was estimated as five times the value of the measured electric conductivity of the soil : water 1 : 5 suspension (Slavich and Petterson, 1993). Only one soil profile for each of the sites at each sampling date was subjected to ion content analysis; cations were measured by atomic absorption spectrophotometer (Hitachi Z5010) and anions by ion chromatograph (Dionex). HCO_3^- was estimated after Wada and Seki (1994) by using measurements of dissolved total organic carbon (Shimadzu TOC-5000A).

Calculations of active-layer depth, leaching and water balance

Salinization is known to change the thermal regime in the active layer, and hence its thickness or depth. Taking this into consideration, the thickness of the active layer because of salinization was estimated according to

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Romanovsky *et al.* (1997; Romanovsky and Osterkamp) using a modified Kudryavtsev equation derived with the assumption of a periodic steady-state temperature regime (Kudryavtsev *et al.*, 1974), which is a result of the Fourier temperature wave propagation theory to materials with phase changes (latent heat greater than zero). In the unsaturated (or vadose) zone, water movement in the form of leaching is given by the Richards (1931) equation expressed in terms of the volumetric soil moisture content θ (cm^3 cm^{-3}) as in Pielke *et al.* (1992):

$$\frac{\partial \theta}{\partial t} = \frac{\partial W_s}{\partial z} \quad (1)$$

where W_s (cm s^{-1}), the moisture flux within the soil, is defined as

$$W_s = D\frac{\partial \theta}{\partial z} + k \quad (2)$$

where D (cm^2 s^{-1}) is the moisture diffusivity and k is the soil hydraulic conductivity. Soil water retention properties needed for calculations were taken from Rawls *et al.* (1991).

Water balance in the active layer was defined as the amount of water from the total input (precipitation plus groundwater recharge) minus the total output (evaporation, transpiration and recharge to permafrost), and considered as equal to soil water storage, which can be determined as a change of volumetric water content.

RESULTS

Seasonal thawing

The thawing soil depth in the F- and S-sites reached around 90 cm by mid August. The thawing layer depth at the AM-site was similar to that in the forest. The deepest thawing layer was at the P-site (150 cm) on the last sampling date (Figure 2). The rate of thawing was faster at the AB- and P-sites. Thawing occurred in the first two months (May and June), except at the intact forest (F-site). Movement of water and salts is hindered by impermeability of frozen soils. On the other hand, high salt content can affect the increase of active-layer depth. Salinization of soil alone causes permafrost temperature increases of ~0·4 °C, and a deepening of the active-layer depth of about 40–60 cm (Table I). However, the effect of salinization is normally combined with vegetation cover and water content changes in alases.

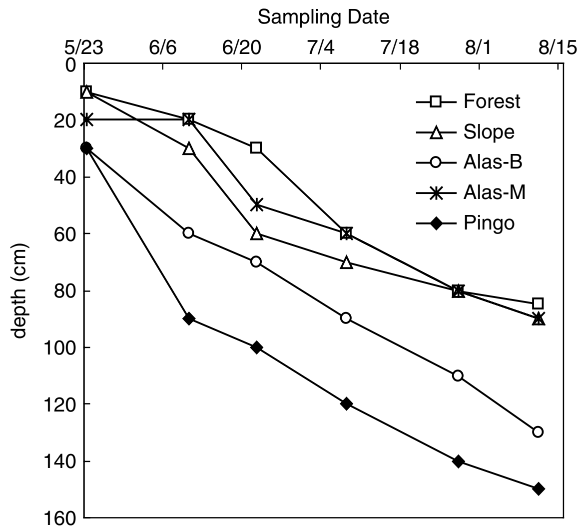

Figure 2. Soil thawing depth variation through the growing season 2005 (May–August). Larch forest (F-site); birch forest (slope, S-site); alas border with *E. repens* as dominant vegetation (AB-site); alas middle with *C. vesicata* as the dominant vegetation; pingo with *E. repens* as the dominant vegetation (P-site)

Soil moisture and water balance

Soil volumetric water content (Figure 3) varied seasonally with snow melting, soil thawing, evaporation, plant transpiration and precipitation. During late May, snowmelt water contributed to higher values of soil moisture in the upper layers (0–20 cm) except for the P-site, where snow had already melted before soil started thawing. Soil moisture changes were governed by rain for the rest of the growing season. Higher variations in soil moisture were observed at the F- and S-sites. The average of soil moisture during the growing season revealed that among the alas sites there are dry (AB- and P-sites) and wet (AM-site) areas. Below 60 cm depth, soil moisture appeared to remain relatively constant for all sites. Water loss was greater in the forest than at alas sites during the summer season. At the P-site, which is the driest of all the sites, the balance was close to zero (Table II). Larch and birch (F- and S-sites respectively) forest water uptake appeared as the main reason for the large difference between forest and alas soil moisture. Despite a higher soil moisture in the alas than in the forest, values of water potential were lower at the AB-site than at the F-site (Figure 4).

Table I. Calculated annual mean temperature of saline soils and active-layer depth for the intact forest (F-site) and dry alas (AB-site)

EC_e (mS cm^{-1})	Salinization[a] (%)	Freezing point (°C)	Thermal conductivity, frozen soil (W m^{-2} K^{-1})	Active layer depth (cm)		Annual mean temperature (°C)
				Meas.	Calc.	
0.1	0·02	−0·1	1·39	1·2–1·3[b]	1·6	−2·0
2.4	0·46	−0·4	1·25	1·8–2·0[b]	1·9	−1·6

[a] Salt weight content.
[b] Data supplied by personnel at Permafrost Institute, Yakutsk.

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Table II. Average of soil volumetric water content, dry soil bulk density and water balance at all sites

Landscape	Site	Water content (vol.%)	Dry bulk density (Mg m^{-3})	Summer total balance[a] (mm)
Forest	F	24·5	1·39	−111·6
Slope	S	28·4	1·32	−78·7
Alas	AB	26·7	1·44	−26·4
	AM	36·3	1·40	−27·4
	P	17·6	1·34	1·1

[a] Equal to water loss.

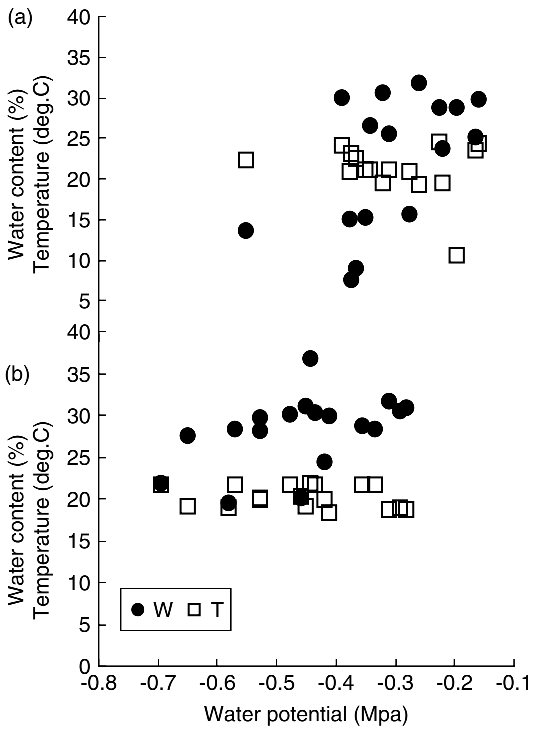

Figure 3. Soil volumetric content versus water potential in the (a) F-site and (b) AB-site

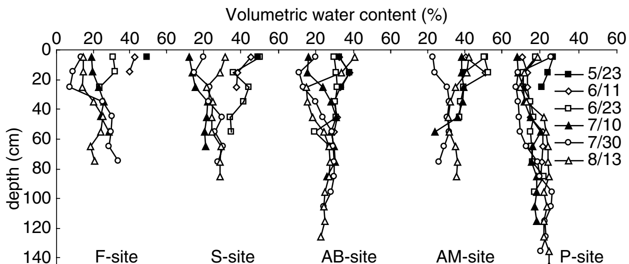

Figure 4. Changes in the soil volumetric water content profile of the F-, S-, AB-, AM- and P-sites during the growing season. All points are the average of two sampling points at each site. Different depths indicate the soil thawing depth for a given sampling date (seven in total)

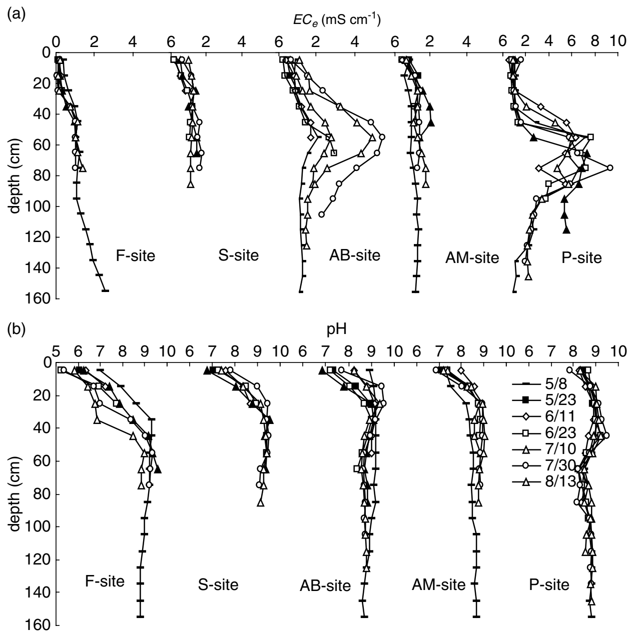

Figure 5. (a) Changes in electric conductivity EC_e and (b) pH in the soil profiles of the F-, S-, AB-, AM- and P-sites. All points are the average of two sampling points at each site. Different depths indicate the soil thawing depth for a given sampling date (seven in total)

Electric conductivity and pH

The values of EC_e, in Figure 5a, revealed different salt distribution patterns at each site. The thawing layer of the F- and S-sites showed almost unchangeable profiles through the growing season, regardless of significant changes in soil moisture at these two sites. Higher values of EC_e were found at the S-site than at the F-site. In alas sites, salt concentration in the soil is as follows: P > AB > AM, which is the same trend as for the thawing depth. Soil becomes saline in midsummer at the AB-site, which is the most representative of alas because of the area it occupies. A peak is present between 50 and 60 cm in the EC_e profile of the AB-site (2·1 mS cm^{-1} in spring, to a maximum value of 5·4 mS cm^{-1} at the end of July) in summer. A peak is also observed at the P-site, which remains at 60 to 90 cm during the whole measurement period (with a maximum value of 9·4 mS cm^{-1}). In contrast to the AB-site, EC_e at the P-site did not vary seasonally, and the profiles in spring and summer show almost the same values. The AM-site, which is wet and shallow in comparison with the other alas sites, shows EC_e values similar to those found at the S-site (from 1·0 to 2·0 mS cm^{-1}).

For the F- and S-sites, pH increased steadily to a depth of around 70 cm (Figure 5b). In larch and birch forests the seasonal change of soil surface pH ranged from 5·1 to 7·1; on the other hand, it ranged from 7·0 to 8·4 at the alas sites and increased to a depth of 30 cm, and then remained almost invariable to the bottom of the active layer.

Soluble ions

Na^+ was the dominant cation in the active layer and upper permafrost of the F-site and the active layer of the AB- and P-sites (deepened after permafrost thawing) in spring, when the soil was still frozen (Figure 6). At the F-site, Na^+ concentrations ranged from 0.13 to 1·62 $mmol_{(c)}\ l^{-1}$ within the active layer (depth ∼1·1 m) and increased from 1·76 to 2·4 $mmol_{(c)}\ l^{-1}$ in the permafrost soils below the base of the active layer to a depth of 160 cm. Na^+ increased with depth, as did all the total soluble cations. The relative proportion of Na^+ with respect to the other cations increased with depth, from 10% at the base of the active layer to over 60% at 110–160 cm depth (upper permafrost). The relative proportion of Na^+ with respect to the other cations also increased with depth, demonstrating the migration capability of the ion. Concentrations of soluble Ca^{2+}, Mg^{2+} and K^+ were higher in permafrost than in the active layer at the F-site. Mg^{2+} concentrations in the active layer were lower than in permafrost. K^+ content did not change with depth, remaining low in the active layer and in the permafrost. At alas sites, in contrast to the forest site, higher concentrations of solutes were found within 1 m of the active layer. At the AB-site, Na^+ concentrations reached 3·6 $mmol_{(c)}\ l^{-1}$ and 3·4 $mmol_{(c)}\ l^{-1}$ at 30 cm and 60 cm respectively, whereas at 160 cm the Na^+ decreased to 1·14 $mmol_{(c)}\ l^{-1}$. Ca^{2+} and Mg^{2+} showed the same trend. K^+ showed an even distribution along the active layer and permafrost. The P-site also showed a peak of salts accumulation in the 60–90 cm soil layer. Ca^{2+} and Mg^{2+} are the most abundant salts at this site. Cl^- in the active layer is low at the F-site and high at alas sites. $SO_4{}^{2-}$ is the most abundant anion at all alas sites, and $HCO_3{}^-$ is evenly distributed all over the active layer. The salt concentration (average of salt concentrations for the last three samples: 11 July, 27 July and 13 August) is low in the active layer of the F-site and S-site, and remained stable during the growing season (Figure 7). In summer, Na^+ ranged from 0·10 to 1·51 $mmol_{(c)}\ l^{-1}$ within the active layer. The salt concentration in the active layer of the S-site is higher than in the intact forest (F-site). The concentrations of Ca^{2+}, Mg^{2+} and $SO_4{}^{2-}$ were particularly high at the S-site. Salt concentration at the AM-site is lower than for the other two alas sites, but cations and anions are higher than in the forest. As at the other alas sites, Ca^{2+}, Mg^{2+}, Na^+ and $SO_4{}^{2-}$ are the prevalent ions at the AM-site. A redistribution of cations and anions was observed at the AB-site. Salts concentrate between 50 and 60 cm at the AB-site: Na^+, 4·68 $mmol_{(c)}\ l^{-1}$; Ca^{2+} 2.98 $mmol_{(c)}\ l^{-1}$; Mg^{2+}, 4·93 $mmol_{(c)}\ l^{-1}$; Cl^-, 0·59 $mmol_{(c)}\ l^{-1}$; $SO_4{}^{2-}$, 6·93 $mmol_{(c)}\ l^{-1}$. At the P-site, the peak of salt concentration remained at the same depth as in spring (60 to 90 cm), with Ca^{2+} as the dominant cation (9·10 $mmol_{(c)}\ l^{-1}$). In general, soils contained Ca^{2+}, Mg^{2+} and Na^+, which are known to have a high base saturation and typically high pH values (Qadir *et al.*, 2001).

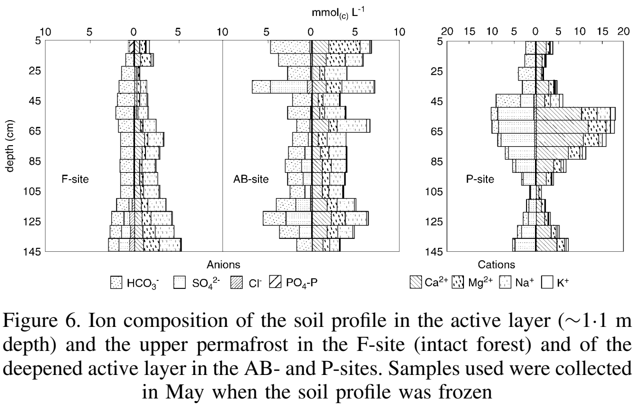

Figure 6. Ion composition of the soil profile in the active layer (∼1·1 m depth) and the upper permafrost in the F-site (intact forest) and of the deepened active layer in the AB- and P-sites. Samples used were collected in May when the soil profile was frozen

DISCUSSION

Origin of salts in the active layer

Soil thawing depth through the growing season indicated that forest (both larch and birch) protected the deepening of the active layer. Temperature regimes at the ground surface beneath forest and open areas are different. However, soil thawing at the AM-site (open area), which represents the wet alas, showed the same variation as in the forest. This indicates that soil thermal parameters (thermal conductivity and latent heat of soil moisture) also play an important role in soil thawing. Higher concentrations of salts in the active layers of the AB- and P-sites indicate that salts formerly trapped in permafrost move upward after thawing, becoming one of the main sources of salts found in the active layer of alas. On the other hand, salt increases the temperature of the active layer (Table I) and creates a positive feedback, increasing the depth of the active layer. Precipitation can also be considered as a major source of soluble salts. The basic components of precipitation in Yakutsk are sulphates (up to 42%) and hydrocarbonates (43–37%), as well as Na^+, Ca^{2+} and Mg^{2+} with total average content from 8·2 to

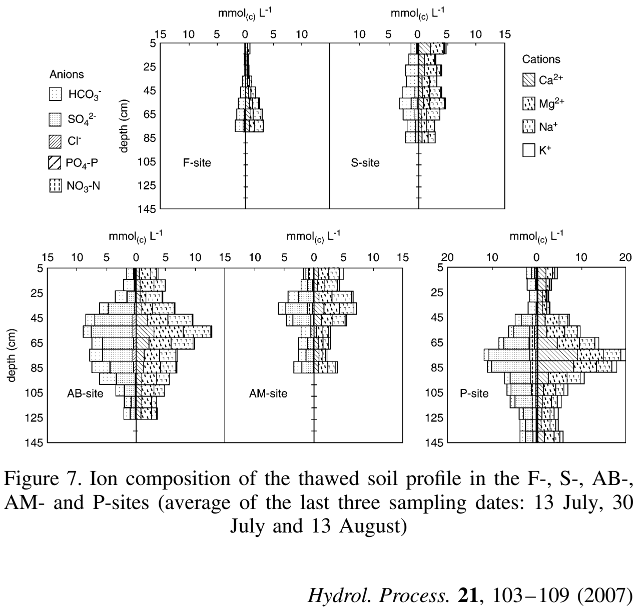

Figure 7. Ion composition of the thawed soil profile in the F-, S-, AB-, AM- and P-sites (average of the last three sampling dates: 13 July, 30 July and 13 August)

18·5 mg l^{-1} and pH 6·5 (State Report, 2002), which is relatively close to the soil chemistry of the active layer. High salt concentrations within the active layer are also associated with larger water accumulation in alases by surface (in spring) and possibly subsoil (in summer) water flows directed to alases from higher forest areas, although Desyatkin (1993) considers subsoil inflow of water into alases because of low soil moisture as unlikely.

Distribution of salts and soil moisture in the active layer

Cation concentrations in permafrost were significantly higher than in the active layer at the F-site; which is also common in the Arctic as a result of leaching effects (Anisimova and Kurchatova, 2000; Brouchkov, 2002). The average pH in the active layer below 30–40 cm both in forest and alas sites was close to 8·4 (range pH 8–9), which is the value of carbonate saturation (Ingle, 1975). Soil moisture variations in the upper soil layers are assumed to be due to root water uptake during the growing season, as explained in Zhang *et al*. (2004). One of the major mechanisms of salt transfer is convection (Iwata *et al*., 1988; Qadir *et al*., 2001); so, salts are going up together with water in the alases, but some amounts are left behind near the point of water absorption as a result of the ion uptake control mechanisms of plants (Carter *et al*., 1975; Tester and Davenport, 2003). Salts are not found in the surface layer because of summer precipitation washing them down. Estimation (Richards, 1931) of soil leaching shows that the wetting front after rain (precipitation of 3 mm) can reach 50 cm depth in a few hours for Yakutsk soil. During summer, because of the intensity of the rain events during the growing season, leaching may happen a few times. The effect that rainwater can have on flushing salts downward is quite well understood (Hardy *et al*., 1983; Mamedov *et al*., 2001). In forest, salts are only minimally redistributed, as water from rain reaching the soil is mostly consumed by larch roots, which predominate in the upper 30 cm of the active layer (Kuwada *et al*., 2002).

Low values of EC_e in the soil profile at 50–60 cm depth at the AB-site were found during spring, suggesting that the salts that have accumulated at this depth increase during the growing season and are washed out during late autumn because of the rain leaching effect (especially during rainy years) and a decrease of evaporative demands (Sugimoto *et al*., 2003). Therefore, the observed salinization of the active layer in alases is secondary, or so-called epigenetic (Cox and Singer, 1986), salinization (i.e. salinization that has occurred later than its immediate host mineral deposits, and has even been permafrost) and happens in summer as a result of spring water collection and high evaporation. The gradual salt accumulation in alases in comparison with forest sites is controlled by the annual balance of salts in the active layer. This same accumulation is responsible for higher values of soil water potential (Hillel, 1980) in the alases compared with the forest (Figure 3).

The hydromorphic stage of development of alases (Bosikov, 1991) has a large influence on the chemical composition of water-soluble compounds in the soils. The increase in salt content happens in a neutral or alkaline environment (the water pH reaches 8·4) with a significant amount of soluble organic matter present. The syngenetic salinization of alases (Desyatkin, 1993) is related to thermokarst development: ice complex melts and soluble ions are retained in the active layer. If even small amounts of salts are leached from the ice complex of 20–60 m thickness and accumulate in the thin active layer, then the syngenetic salinization of alas soils is unavoidable. The ancient syngenetic salinization is unstable in the case of climatic change, watering, thawing of permafrost, and erosion; in contrast, however, modern epigenetic salinization keeps soils saline. The salt content of the active layer of modern thermokarst depressions at the Neleger site does not exceed 0·6%.

Water balance and salts

Evaporation from the surface of areas where natural vegetation has been changed, when repeated annually over a long time, is suggested to produce high salt concentrations in the upper layer of soil (Conacher, 1990; Shimojima *et al*., 1996) in alases. However, water loss is much higher in forest than in alas areas, and there is no accumulation of salts at the F-site. According to Pavlov (1984), evapotranspiration in alases is about 157–207 mm, and in forests during the summer season it is 270–290 mm. Thus, the activity of tree roots taking up water with low salt concentration, the absence of a water supply from the surrounding areas, and the maintenance of a shallow active layer (non-thawing of salt-rich permafrost) could be responsible for the low EC_e values in forests. Salinization increases in alases and, together with soil moisture increase, causes vegetation change, creates a positive feedback, permafrost thawing, and acceleration of thermokarst formation (Brouchkov *et al*., 2004). Reforestation has not been observed in alases due to the salt-sensitive characteristics of larch and birch trees (Desyatkin, 1993).

CONCLUSIONS

Disturbances changed the water and salts distribution in the active layer of former forest turned into saline grasslands in central Yakutia, eastern Siberia. There are substantial differences between water content and electrical conductivity of soils in forests and alases. As soon as a thermokarst has developed and an alas is formed, the transport of ions to upper layers, salinization and alkalinization occur over time. The observed modern salinization of the active layer in alases is epigenetic; this happens in summer as a result of spring water collection and high evaporation. The gradual salt accumulation in alases, in comparison with forests, is controlled by the annual balance of salts in the active layer. Larch forests are characterized by significant summer water loss but small salts content and their stable distribution.

At present, climatic trends point to a steady increase of air and ground temperatures in northern areas where permafrost is distributed. If the threshold is reached when permafrost starts to thaw from its top down, then one of the important changes in the active layer will be the increase in salt content to the point where reforestation will be impossible.

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