Salt and water movement in a Forest-Alas ecosystem in Central Yakutia, Eastern Siberia

Larry Lopez [1,*], Anatoli Brouchkov[1], Hiroyoshi Nakayama[1], Fumiaki Takakai[2], Alexander N. Fedorov[3] and Masami Fukuda[1]

[1] *Institute of Low Temperature Science, Hokkaido University, Kita 19 Nishi 8, Kita-ku, Sapporo 060-0819, Japan.*
[2] *Graduate School of Agriculture, Hokkaido University, Japan.*
[3] *Permafrost Institute, Siberian Branch, Ras, Yakutsk, Russia.*

[*] *Corresponding author: larry@lowtem.hokudai.ac.jp*

1. INTRODUCTION

In Eastern Siberia, "continental" salinization is caused by predominance of evaporation above precipitation as well as 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). Active layer salt content may indicate the impact of climate warming and active layer deepening (Wolfe et al., 2000). In Central Yakutia alone there are about 16000 alases with a total area of 44 million ha. Modern disturbances and recent climatic changes continue to cause active layer deepening and activation of young thermokarsts depressions by the thawing of upper ground ice on stable areas of inter-alas meadows (Fedorov and Konstantinov, 2003). 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 et al., 1999). 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 the seasonal movement of water and salts in the active layer.

2. MATERIAL AND METHODS

2.1 Site description

Neleger Experimental Station is located 30 km north-northwest from the city of Yakutsk (62º 05' N, 129º 45') and belongs to the Yakutsk Permafrost Institute. The area consists of a group of Lena River terraces with elevations of 200-220 m.a.s.l. The bedrock predominantly consists of limestones and argillites. 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). Samples were collected in five locations of a forest - alas transect with a depression from the forest to the alas of approximately 3 meters, and consisted of the following dominant vegetation: *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 alas, AM-site) and *Elytrygia repens* (in the pingo, P-site). Two soil samples were collected approximately every two weeks at each location, starting in May 2004.

2.2 Soil moisture and chemical analysis

Soil moisture of the thawing soil layer was determined gravimetrically. Soil water potential was measured in June and July in the F- and AB-site from the surface to the maximum soil depth. Electric conductivity and pH were measured (Page et al., 1982) for all soil profiles from

Symptom of Environmental Change in Siberian Permafrost Region,
Eds. Hatano R and Guggenberger G, p 233-240, Hokkaido University Press, Sapporo, 2006

each sampling site. Electric conductivity of saturated paste (EC_e), used to evaluate saline and alkaline soils was estimated according to Slavich PG & Petterson GH (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 and anions by ion-chromatograph. HCO_3^- was estimated after Wada & Seki (1994).

2.3 Water balance

Water balance in the active layer was defined as the amount of water from the total input (precipitation + 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.

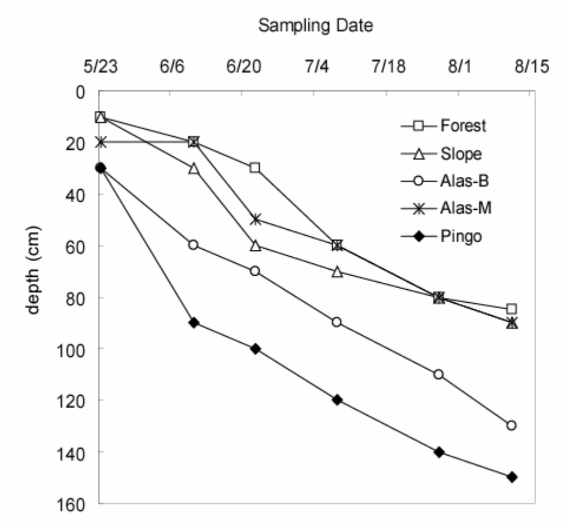

Fig. 1. Soil thawing depth variation through the growing season 2004. Larch forest (F-site); Birch forest (Slope, S-site); Alas Border (AB-site); Alas Middle (AM-site) and Pingo (P-site).

3. RESULTS

3.1 Seasonal thawing, soilmoisture and water balance

The thawing soil depth in the F- and S-site 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 in the P-site (150 cm) on the last sampling date (Fig. 1). The rate of

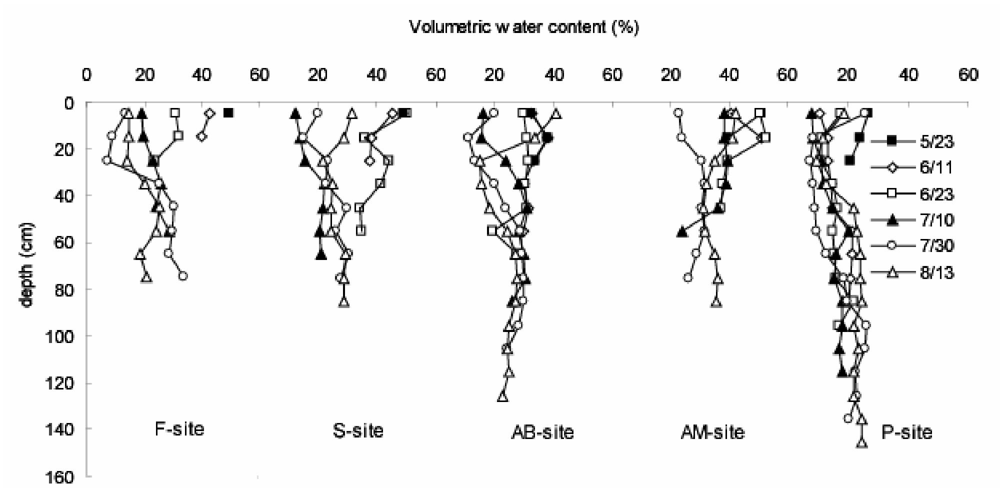

Fig. 2. Changes in the soil volumetric water content profile of the F-, S-, AB-, AM- and P-site during the growing season. All points are the average of two sampling points at each site. Different depths indicate the soil thawing depth for a given sampling date (Seven in total).

thawing was faster in the AB- and P-site. 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.

Soil volumetric water content (Fig. 2) 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 in the F- and S-site. The average of soil moisture during the growing season revealed that among the alas sites there is a dry (AB- and P-site) and wet (AM-site) area. Below 60 cm depth, soil moisture appeared to remain relatively constant for all sites. Water loss was bigger in the forest, than in alas sites during the summer season. In the P-site, which is the driest of all the sites, the balance was close to zero (Table 1). Larch and birch (F- and S-site respectively) forest water uptake appeared as the main reason for the large difference between forest and alas soil moisture. Despite of higher soil moisture in alas than in the forest, values of water potential were lower in the AB-site (0.3-0.7) than in the F-site (0.2-0.4).

Table 1. Average of soil volumetric water content, dry soil bulk density and water balance at all sites.

Landscapes	Sites	Volumetric water content (%)	Dry bulk density ($Mg\ m^{-3}$)	Summer total balance (equal to water loss) (mm)
Forest	F	24.5	1.39	-111.6
Slope	S	28.4	1.32	-78.7
	AB	26.7	1.44	-26.4
Alas	AM	36.3	1.40	-27.4
	P	17.6	1.34	1.1

3.2 Electric conductivity and pH

The values of EC_e, in Fig. 3a, revealed different salt distribution patterns at each site. Higher values of EC_e were found in the S-site compared to 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. 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. In the P-site a peak is also observed, which remains at 60 to 90 cm during the whole measurement period (with a maximum value of 9.4 $mS\ cm^{-1}$). The AM-site, which is wet and shallow in comparison to the other alas sites, shows EC_e values similar to those found in the S-site (from 1.0 to 2.0 $mS\ cm^{-1}$).

For the F- and S-site, pH increased steadily to a depth of around 70 cm (Fig. 3b). In larch and birch forests the seasonal change of soil surface pH ranged from 5.1-7.1; on the other hand, it ranged from 7.0 to 8.4 in the alas sites and increased to a depth of 30 cm, and then remained almost invariable to the bottom of the active layer.

3.3 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-site (deepened after permafrost thawing) in spring, when the soil was still frozen . At the F-site, Na^+ concentrations ranged from 0.13 to 1.62 $mmol_{(c)}\ L^{-1}$ within the active layer (depth approx. 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. The relative proportion of Na^+ with respect to other cations increased with depth, from 10% at the base of the active layer to over 60 % at 110 to 160 cm depth (upper permafrost). The relative proportion of Na^+ with respect to other cations also increased with depth, demonstrating the migration capability of the ion.

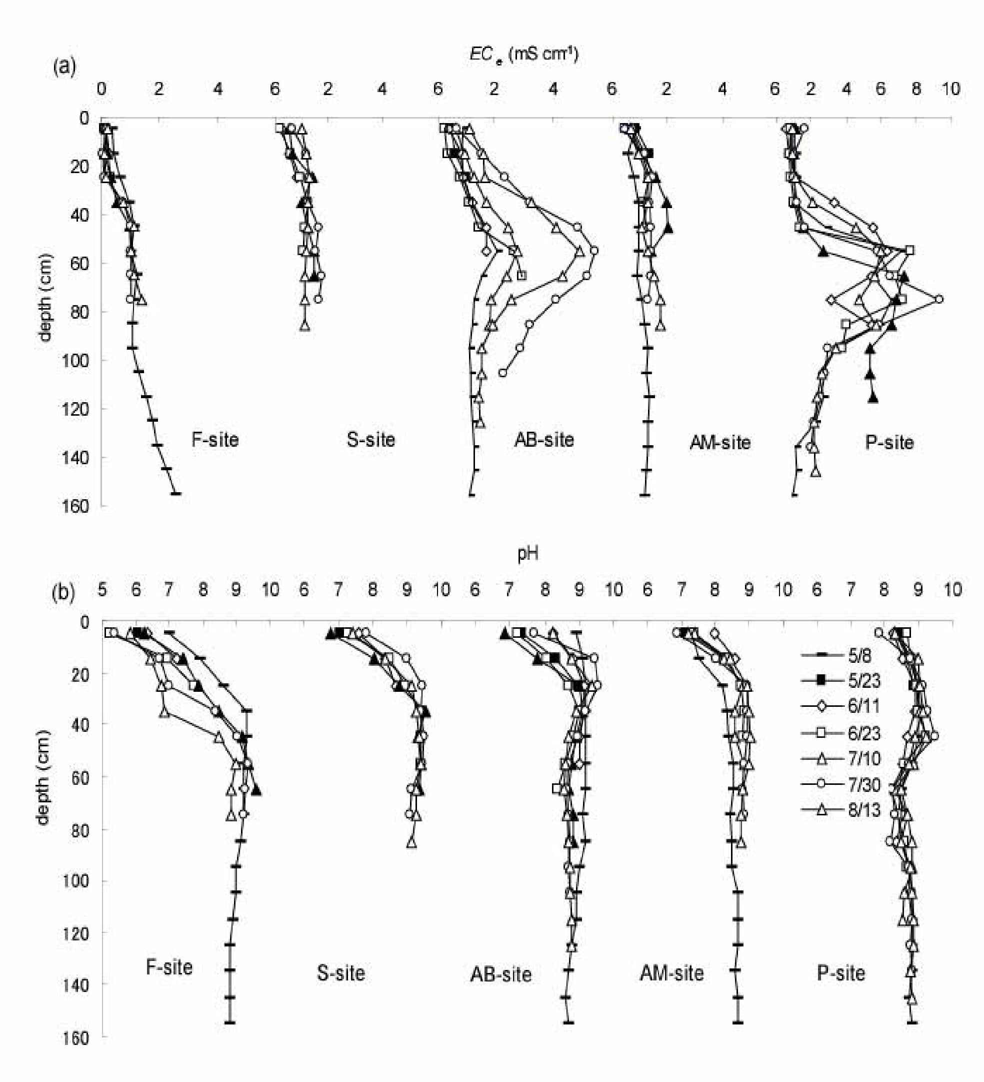

Fig. 3. (a) Changes in electric conductivity (ECe) and (b) pH in the soil profile of the F-, S-, AB-, AM- and P-site. All points are the average of two sampling points at each site. Different depths indicate the soil thawing depth for a given sampling date (Seven in total).

Concentrations of soluble Ca^{2+}, Mg^{2+}, and K^+ were higher in permafrost than in the active layer in the F-site. Mg^{2+} concentrations in the active layer were lower than in permafrost. K^+ content did not change with depth and remained low in the active layer and in the permafrost. In alas sites in contrast to the forest site, higher concentrations of solutes were found within 1 meter of the active layer. In the AB-site, Na^+ concentrations reached 3.6 and 3.4 $mmol_{(c)}$ L^{-1} at 30 and 60 cm respectively, while at 160 cm 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.

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 in this site. Cl^- in the active layer is low in the F-site and high in alas. SO_4^{2-} is the most abundant anion at all alas sites and HCO_3^- is evenly distributed all over the active layer. Salt concentration (average of salt concentrations for the last three samples: July 11, July 27 and Aug 13) is low in the active layer of the F-site and S-site, and remained stable during the growing season (Fig.4). In summer Na^+ ranged from 0.10 to 1.51 $mmol_{(c)}$ L^{-1} within the active layer. Salt concentration in the active layer of the S-site is higher than in the intact forest (F-site). Concentration of Ca^{2+} and Mg^{2+} and SO_4^{2-} were particularly high in the S-site. Salt concentration in the AM-site is lower than in the other two alas sites, but cations and anions are higher than in the forest. Salts concentrate between 50 and 60 cm in the AB-site, namely; Na^+, Ca^{2+} and Mg^{2+} (4.68, 2.98 and 4.93 $mmol_{(c)}$ L^{-1} respectively) as well as Cl^- and SO_4^{2-} (0.59 and 6.93 $mmol_{(c)}$ L^{-1}). In 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}).

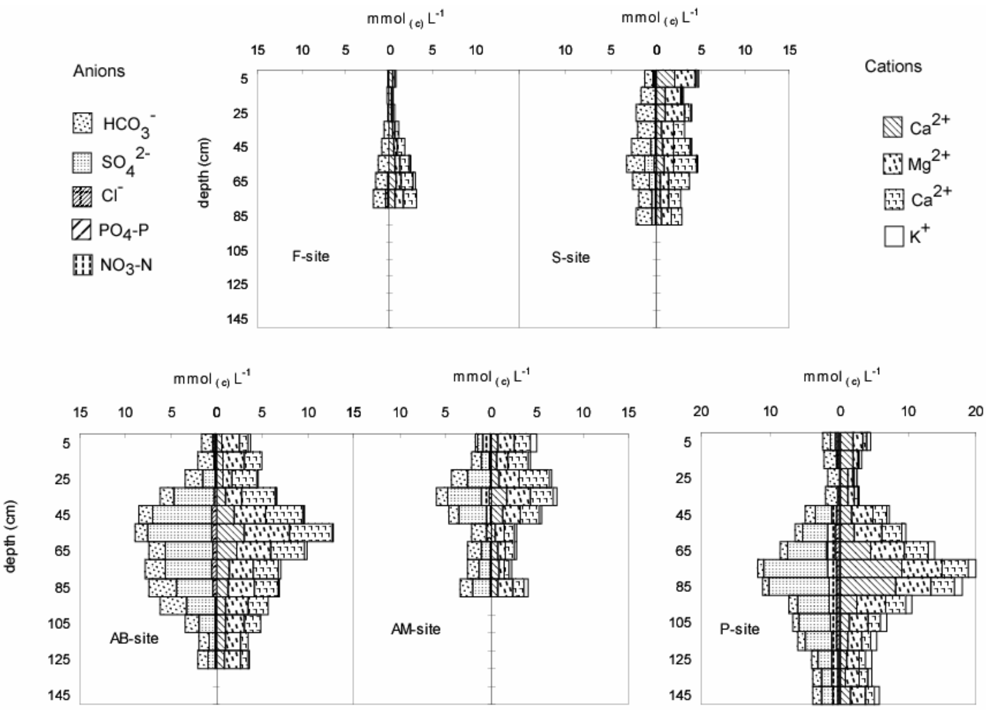

Fig. 4. Ion composition of the thawed soil profile in the F-, S-, AB-, AM- and P-site (average of the last three sampling dates: July 13th, July 30th and Aug 13th).

4. DISCUSSION

4.1 Origin of salts in the active layer

Soil thawing depth along the growing season indicated that forest (both larch and birch) protected the deepening of the active layer. Higher concentrations of salts in the active layer of the AB- and P-site indicates 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 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 18.5 mg/l and pH of 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 alas by surface (in spring) and possibly subsoil (in summer) water flows directed to alas from higher forest areas, although Desyatkin (1993) considers subsoil inflow of water into alases because of low soil moisture as unlikely.

4.2 Distribution of salts and soil moisture in the active layer

Cation concentrations in permafrost were significantly higher than in the active layer in the F-site; which is also common in the Arctic as a result of leaching effects (Anisimova and Kurchatova, 2000; Brouchkov, 2002). The pH range of 8-9, in the active layer below 30-40 cm both in forest and alas sites, was close to 8.4, 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 Xiying et al (2004). One of the major mechanisms of salt transfer is convection (Iwata et al., 1988; Qadir et al., 2001). Salts are not found in the surface layer because of summer precipitation washing salts down. 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.

The gradual salt accumulation in alas in comparison to 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 in the Alas compared to the forest.

The hydromorphic stage of development of alases (Bosikov, 1991) has a large influence on the chemical composition of water-soluble and chemical 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 a small amount of salts is leached from the ice complex of 20-60 m thickness and accumulates in the thin active layer, the syngenetic salinization of alas soils is unavoidable. However, the ancient syngenetic salinization is unstable in the case of climatic change, watering, thawing of permafrost and erosion; whereas in contrast, modern epigenetic salinization keeps soils saline. Salt content of the active layer of modern thermokarst depressions in Neleger site does not exceed 0.6%.

4.3 Water balance and salts

Evaporation from the surface repeated annually over a long time, of areas where natural vegetation has been changed, is suggested to produce high salt concentrations in the upper layer of soil (Conacher, 1990; Shimojima et al., 1996) in alas. However, water loss is much higher in forest than in alas areas, and there is no accumulation of salts in the F-site. Then activity of tree roots uptaking water with low salt concentration, absence of water supply from surrounded areas and the maintenance of a shallow active layer (non-thawing of salt rich permafrost) could be responsible for low EC_e values in forests. Salinization increases in alases, and together with soil moisture increase, causes vegetation change, creates positive feed back, permafrost thawing and acceleration of thermokarst formation (Brouchkov et al. 2004). Reforestation has not been observed in alas due to the salt-sensitive characteristic of larch and birch trees (Desyatkin, 1993).

5. CONCLUSION

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 soil in forest and alas. As soon as thermokarst has developed and alas is formed, the transport of ions to upper layers, salinization and alkalinization occur over the time. Observed modern salinization of the active layer in alas is epigenetic, and happens in summer as a result of spring water collection and high evaporation. The gradual salt accumulation in alas in comparison to forest is controlled by annual balance of salts in the active layer. Larch forests are characterized by significant summer water loss but small salt content and their stable distribution.

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