THE EFFECT OF CRYOGENIC LANDSLIDES (ACTIVE-LAYER DETACHMENTS) ON FERTILITY OF TUNDRA SOILS ON YAMAL PENINSULA, RUSSIA

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Abstract: Tundra vegetation and soils have spotty-spatial correlated pattern caused by the activity of geomorphic processes in the active layer, especially cryogenic landslides (active layer detachments). The landslides on Yamal Peninsula periodically renovate slopes of the dissected Middle-Upper Pleistocene marine plain, removing washed out (desalinized) active layer soils, and exposing saline marine deposits at the surface of concave slopes. Both convex slopes and hilltops are stable, undisturbed, bearing initial mature vegetative cover on well-washed-out, mostly sandy soils.

Landslides turn back the clock on vegetation establishment and pedogenesis. Newly exposed shear surfaces are subject to pioneer re-vegetation and soil formation. Activity of these processes is facilitated by higher nutrition content in the active layer represented by marine saline deposits. Landsliding started at least 2 thousand years ago. Old landslides (centuries to several millennia old) increase site productivity. Higher biomass compared to non-landslide terrain is due to dominance of grasses over mosses and expansion of high willows.

INTRODUCTION

In the Typical Tundra bioclimatic subzone the most destructive process affecting the active layer is landsliding. Cryogenic landslides are widespread on the Yamal and Gydan Peninsulas, on the Taimyr coast of the Yenisey Gulf, Russia (from Dixon to Cape Shaitansky), as well as on the islands of the Canadian Arctic Archipelago (Burn & Friele 1989; French 1996; Harry & Dallimore, 1989; Harris & Lewkowicz, 1993; Leibman 1995; Leibman & Egorov 1996; Ukraintseva 1997; and many others).

Landslides on Yamal Peninsula periodically modify slopes of the dissected Middle-Upper Pleistocene marine plain, by removing washed out active layer soils, and bringing saline marine deposits to the surface. Landslides produce concave and convex slopes. Convex slopes are undisturbed, bearing mature vegetative cover on well-washed soils. Concave slopes are those transformed by repeated landslides. Mesorelief is presented by cascades of shear surfaces alternating with lumpy landslide bodies. Often numerous multi-aged landslides often join to form semi-bowl-shaped depressions (landslide cirques).

Undisturbed surfaces are characterized by rather homogenous grain-size composition, dominated by silts (70-80%). In contrast, landslide slopes are clayey-sandy. The younger the landslide shear surface, the more clayey the soils.

Our long-term observations on Yamal Peninsula after the abundant landsliding of 1980-s show that the first several decades after the landslide event, vegetation is still very sparse on the shear surfaces, soil cover has not yet formed. Bare clayey surfaces are saline with evaporates, and are sparsely covered by Gramineae and chamomile during dry periods (Rebristaya et al. 1995). Desalinization of the active layer starts immediately after the landslide event. Migration of ions to the surface, and then washing away of evaporates by rain water and surface runoff are the main mechanisms of desalinization (Leibman & Streletskaya, 1997; Streletskii et al. 2003). Subsurface runoff also contributes to washing of...
saline deposits. The latter is due to post-cryogenic fissuring at the active-layer base that causes high permeability in clayey deposits (Leibman et al. 2003).

The landslide process in the Typical Tundra of Yamal Peninsula that started at least 2000 years ago (Leibman et al. 2003) results in the increase of soil fertility and vegetation biomass. We attempt to show that soil and vegetation productivity is higher on landslides than adjacent non-slide (undisturbed) terrain. The transformation of soils and vegetation, and the change of their geochemical properties caused by the landslide activity are responsible for higher soil fertility on old landslide slopes compared to undisturbed surfaces. Laboratory tests on the samples collected in key landslide cirques were analyzed.

STUDY AREA AND METHODS

The Central Yamal Peninsula (Figure 1) has a highly dissected plain in the Typical Tundra bioclimatic subzone. Continuous permafrost with a rather thick (0.8-1.2 m) active layer of sandy and clayey soils, often saline due to marine origin, typifies the plain. Tundra moss-lichen-grass vegetation here is complicated by vast areas of high willow shrubs, not found elsewhere at the same latitude and bioclimatic subzone. This distinct vegetation type results from recurrent surface disturbance by landslides.

Studies were undertaken within 4 key landslide cirques: semi-circle catchments formed by multi-aged landsliding (Figure 2). Previous studies indicated that landslide events recognized from the shear surfaces, occurred 10-30 (young landslides), and 300 to 2100 (old landslides) years ago (dated by radiocarbon in the Geological Institute of Russian Academy of Sciences, Leibman et al. 2003).

Generic soil horizons were sampled continuously in pits along transects at 10 landslides across 4 landslide cirques. Vegetation was sampled at 1-3 m² plots located above the soil pits. Ground-water samples were collected in the soil pits after 1-2 days of water seeping from the pit walls.

The grain size, main ions in filtered soil water extraction, as well as humus, organic matter, mobile P and N were determined according to the State Standards (1992, 1984, 1980). Air dried and homogenized soil and plant samples were analyzed by XRF spectrometers ORTEC-TEFA.
Laboratory data were compiled into a cryogeochemical database. Data were analyzed within the subdivided landscape units: undisturbed hilltops, undisturbed (convex) slopes (A), and landslide-affected slopes (B – shear surfaces and C – landslide bodies). Undisturbed surfaces have the most mature soil and vegetation of the landscape units. Landslide slopes in their turn are subdivided by age into: young (several years to few decades, B1 and C1), and old (centuries to millennia, B2 and C2). The database includes results of analyses and textual descriptions for deposits, soil, vegetation and water (including grain size, geochemical and agrochemical properties).

**MAIN RESULTS AND DISCUSSION**

Long-term land-based observations by the authors since 1988 after the abundant landsliding along with remote-sensing data interpretation show that the first several decades after the landslide event, vegetation is still very sparse on the shear surfaces, and soil cover has not yet formed (Rebristaya *et al.* 1995; Leibman *et al.* 2000). Bare clayey surfaces, during dry periods, show evaporate crystals and are sparsely covered by Gramineae and chamomile. Desalinization of the active layer starts immediately after the landslide event due
to migration of ions to the surface and to the active-layer base (Leibman & Streletska, 1997; Streletskii et al. 2003). Evaporates on the surface are washed away by rain water and surface runoff. Salts accumulating at the active-layer base are washed away by subsurface runoff through the highly permeable horizon caused by post-cryogenic fissuring. Re-vegetation and soil formation does not start until the salinity of the active layer is reduced to a certain level. The necessary desalinization may take several years or decades to occur.

On the undisturbed surfaces not subject to landsliding, soil cover is developed in sandy-silty deposits to the depth of 40-50 cm. Vegetation is represented by undershrub-moss-lichen communities.

In contrast, landslide-affected slopes are represented by sandy-silty deposits in the landslide bodies and clayey deposits on the shear surfaces. Soil is developed, depending on the age of a landslide, to the depth of 0.5 to 30-40 cm. Vegetation cover ranges from pioneer meadow communities on the young shear surfaces to willow shrubs with grasses and moss/grasses surface cover on the old ones.

The undershrub/grass/moss and moss/lichen communities are the background vegetation of the Typical Tundra subzone. They dominate hilltops and undisturbed slopes (A3) in the studied region. On the undisturbed surfaces mosses cover about 100%, and willow cover less than 10-15% of the area.

Landslide processes influence the seral stages of vegetation. After some years following the landslide event, the young shear surfaces become colonized with pioneer herbs alternating with still bare spots. The second stage is colonization by meadow sedge/grass communities with active willow recruitment. High willow communities occupy the oldest landslide slopes. Willow associations are dense on the old landslide bodies and are sparse on the shear surfaces of the same age.

On the old landslide-affected slopes the willow coverage increases up to 50-80%, and less than 80% is covered by mosses. Total phytomass on old and old landslide slopes is 1.5-2 times higher then on hilltops. Thus, high and productive willows grow on unstable landslide-affected slopes (Ukraintseva & Leibman, 2000; Ukraintseva et al. 2000, 2003).

**Grain size**

Grain size distribution in the active-layer deposits influences soil morphology, water permeability/saturation, ion absorption, salinity and rate of desalinization. Grain-size data from multi-aged surfaces sampled in the upper and middle portions of the active layer are compared at the diagrams (Figure 3).
Figure 3. Generalized grain-size data at the landslide cirques of the research station “Vaskiny Dachi”: D, a particle diameter; A, an undisturbed surface; B1, a shear surface; C1, a landslide body, both at a young landslide; and B2, the shear surface; C2, the landslide body, both at an old landslide. Dotted line is for the upper 20-cm horizon, and solid line represents the horizon below 50 cm.

The grain-size composition in the active-layer of the watershed (oldest) surface appeared to be rather uniform. The silty fraction, comprised of mainly coarse silt particles makes up 40-60% of the samples (Figure 3A). The portion of the fine and small-grain sand fraction is slightly less and reaches 30-50%. The clay particle fraction does not exceed 10%. Grain size distribution within the section is rather even and the upper horizons are close in grain size composition to the lower ones contacting with permafrost.

The young landslides however are completely different in grain size composition and are characterized by the domination of clay particles (40-60%) and high lateral differentiation between the shear surfaces (B1) that are more clayey as compared to the landslide bodies (C1).

Maximum heterogeneity in grain size composition both laterally and vertically is found on the oldest slopes that underwent repeated landsliding resulting in superposition and mixture of clayey (shear surface) and sandy (landslide body) soils and rocks.

Cryogeochemical properties of the landscape units

Cryogeochemical properties of soils found in Table 1 show the following.

- The soils of the undisturbed surfaces are weakly acid throughout the whole profile with a slight increase in pH at the depth of 21-25 cm (pH=6.53, Ap horizon). Minimum pH value is found in gley horizon G at the depth of 14-21 cm (pH=5.88). Ion concentration in the soil water extraction from different horizons is very low and
maximum values do not exceed 0.048% (horizon Ap, depth 3-12 cm). Small increases in ion concentration (up to 0.015 %) can be traced in the gley G horizon at the depths 25 cm to 40 cm. Therefore the soils of the undisturbed surfaces (“background” soils) are characterized by weak acidity, low ion concentration in water extractions, low humus, with water soluble mineral compounds accumulation above the permafrost table.

- The soils of young shear surfaces are generally of rather uniform seasonally thawed clay matter. The examined profile of clay deposits has a weakly alkaline or alkaline pH. In some cases the upper layers may be neutral with the deeper layers slightly alkaline. Compared to background (undisturbed) soils the young clayey shear surfaces are enriched in water soluble mineral compounds that increase with depth. Ion concentration in soil water extraction reaches 0.2% at the depth of 60-65 cm and in some cases it has a similar value next to the surface. Despite the visual absence of organic matter in clays the humus content at the depth of 5-20 cm reaches 1.3% reducing to 0.7% at 25-40 cm (Table 1). Organic matter may be the product of microbiological activity, or be the relics of buried old soils crumbled while sliding. Therefore the soils of the young landslide shear surfaces are noted for weakly acid and acid pH values and relatively high content of water soluble mineral compounds (up to 0.2 %). These peculiarities are likely to be due to a weak washing out of the recently exposed saline marine deposits by rain water. The soils of the young landslide bodies are characterized by a neutral pH that can increase with depth up to pH=8 (Table 1) towards the clayey deposits of the shear surface. Ion concentration in water extraction from dried soils is low and does not exceed 0.075% in the Ap horizon. A slight increase in ion concentration is found also in the underlying deposits (D, up to 0.067%).

- On the old shear surfaces pH conditions in soils vary from weakly acid and neutral to weakly alkaline. The total amount of water soluble mineral compounds changes from that close to the background values (0.009-0.085% to 0.57 %). The soils of the old landslide bodies have presumably neutral pH and a non-uniform vertical profile. They often have single or several buried organic layers with weakly acid pH and increased ion concentration. Vertical differentiation of the soil profile developed on the old landslide bodies reflects the mixing of the soil mass during landsliding. Similar differences in pH have been noticed by Geertsema and Pojar (in press) in a glaciomarine landslide in northwestern British Columbia.
Table 1. Some soil and plant properties at the key landslide cirque of the research station “Vaskiny Dachi”

<table>
<thead>
<tr>
<th>Landscape units</th>
<th>Soil data</th>
<th>Plant data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total salinity* %</td>
<td>pH</td>
</tr>
<tr>
<td>Undisturbed hilltop</td>
<td>0.02</td>
<td>6.2</td>
</tr>
<tr>
<td>Undisturbed slopes</td>
<td>0.02</td>
<td>6.7</td>
</tr>
<tr>
<td>Old landslide body</td>
<td>0.03</td>
<td>7.02</td>
</tr>
<tr>
<td>Old landslide shear surface</td>
<td>0.04</td>
<td>7.12</td>
</tr>
<tr>
<td>Young landslide body</td>
<td>0.10</td>
<td>7.4</td>
</tr>
<tr>
<td>Young landslide shear surface</td>
<td>0.28</td>
<td>7.8</td>
</tr>
</tbody>
</table>

* Determined as total ion concentration in water extraction related to 100 g of dry soil matter

**Agrochemical properties of the tundra soils**

The nitrogen and humus content of soils on landslide-affected areas also show high variability compared to background levels. The undisturbed soils of hilltops are characterized by weak acidity (pH=5.5-5.8), low nitrogen concentration (0.08-0.18%), rather high organic carbon (1.5-2.3%), and very low saturation with bases (4.5%). Humus concentration amounting to 2.9% in gley G horizon at the depth of 10-12 cm drops to 1.3% at 23 cm. In the lower layers the concentration of organic matter slightly increases to 1.7% due to its weak concentration over the permafrost layer.

Humus percent increases with depth from 2.3% (G horizon, 10-30 cm deep) to 3.5% (the same horizon, 55-60 cm) due to the burial of organic matter (peaty layer Ap) and “retinization” over the permafrost table (Table 1).

In old landslides (over 1000 years old, Leibman et al. 2000) the soil cover restores. Soils reduce both in pH (down to 6.5) and in base saturation (to 24.5 %) that verifies gradual desalination of the active layer approximating background conditions. High willow shrubs covering old landslides increase organic carbon and nitrogen content in the soil by 2 times on average, thus improving its productivity (Ukraintseva et al. 2003).

Discussed patterns associated with the rich willow leaf-littered soils correlate with results observed by Jumponen et al. (1998) at Lyman Glacier forefront in the Cascade Range, USA. Their data indicate that soil nitrogen and soil organic matter under willows may be 3 to more than 10 times higher compared to the soils beyond the willow canopies.
Table 2. Fertility of the tundra soils

<table>
<thead>
<tr>
<th>Landscape units</th>
<th>Statistic parameter</th>
<th>pH</th>
<th>N, %</th>
<th>C, %</th>
<th>Humus, %</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undisturbed hilltop</td>
<td>mean</td>
<td>5.87</td>
<td>0.10</td>
<td>2.00</td>
<td>3.45</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>stand. deviation</td>
<td>0.67</td>
<td>0.04</td>
<td>0.34</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>6.45</td>
<td>0.18</td>
<td>2.23</td>
<td>3.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>4.95</td>
<td>0.06</td>
<td>1.51</td>
<td>2.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>7.67</td>
<td>0.13</td>
<td>0.90</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>Young landslide</td>
<td>stand. deviation</td>
<td>0.50</td>
<td>0.08</td>
<td>0.49</td>
<td>0.79</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>8.40</td>
<td>0.31</td>
<td>1.51</td>
<td>2.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>6.85</td>
<td>0.03</td>
<td>0.24</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>6.72</td>
<td>0.24</td>
<td>2.86</td>
<td>5.26</td>
<td></td>
</tr>
<tr>
<td>Old landslide, willow shrub</td>
<td>stand. deviation</td>
<td>0.58</td>
<td>0.15</td>
<td>2.62</td>
<td>4.79</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>7.70</td>
<td>0.56</td>
<td>7.48</td>
<td>12.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>5.65</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

The main agrochemical parameters organic carbon and nitrogen are shown in figure 4. It can be noted that organic carbon in the old landslides approaches that of the undisturbed (most old) surfaces, while on the young landslides this parameter is much lower. On the young landslides, the distribution of organic carbon in profile is rather uniform, indicating recent exposure of non-organic deposits. In contrast, on the undisturbed surfaces organic carbon is rather high at the top of the profile, decreases with depth, and accumulates at the active-layer base.

Figure 4. Vertical distribution of organic carbon (Corg) and nitrogen (N) for various landscape units: A, an undisturbed surface; B1, a young landslide shear surface; B2, an old landslide shear surface.
Accumulation of organic carbon at the active-layer base of the undisturbed units is due to washing of soluble organic carbon by aggressive ground waters, filtering through saline sediments. Existence of two accumulation zones for soluble salts (geochemical barriers) was noted at the shear surfaces of modern landslides (Leibman & Streletsksaya, 1997; Streletskii et al. 2003). In the old landslide, organic carbon is even higher at the top of the section because of more active soil processes at the shear surfaces as explained above, and decreases with depth. Accumulation at the active-layer base is not as pronounced as for the undisturbed surfaces, possible because of an unstable permafrost table in clayey soils, turbation during landsliding, and so on.

The pattern for Nitrogen distribution with depth (figure 4) for the undisturbed surface is the same as for organic carbon – two zones of accumulation at the top of the profile, and at the active layer base. Most remarkable is a much higher N concentration at the landslide shear surfaces compared with the undisturbed ones. For young landslides this is mainly due to salinization of the newly formed active layer, while at the old shear surface this is a combined effect of mineralogical and biogenic processes in the active layer.

The highest concentration of organic carbon and N at the top of the soil profile typical for the old shear surfaces can be explained by the effect of saline parent deposits, that increase re-vegetation by herbs, which in its turn, provides better conditions for willow shrubs development and enrichment of soils with leaf litter.

CONCLUSION

Analysis of the data indicates a relationship between landslide disturbance age and soil fertility. Desalination of old marine sediments after the landslide event leads to active layer enrichment with water-soluble salts, which supply plants with nutrition, provide active re-vegetation with herbs, and re-formation of soils, followed by willow shrubs expansion.

Willow shrubs are is the main reason for increased biodiversity and biological productivity. They provide more nutrition than typical-tundra vegetation like moss-lichen-grass communities, due to the leaf litter.

Striking differences in the agrochemical indicators are observed between stable undisturbed surfaces and landslide-affected slopes of various ages. The soil of hilltops is characterized by low acidity (pH=5.5÷5.8), low nitrogen content (0.08-0.18%), rather high organic carbon (1.5-2.3%), and very low base saturation (4.5%). Young landslide surfaces have a much higher base saturation (50-100%), pH increases up to 7.5-8.0, and organic carbon content is low (0.2-0.7%). On old landslides, high willow thickets occupy old shear surfaces due to additional nutrients and high winter snow cover, and thus, increase biomass. On 1000-2000-year old landslides, soils show gradual reduction both in pH (down to 6.5) and in base saturation (down to 24.5 %) that indicates continuing desalination of the active layer deposits towards the background conditions. Organic carbon and nitrogen concentration in soils increase twice on the average, thus improving soil fertility.

To sum up, landslides that started more than 2000 years ago result in increased soil fertility and biomass in modern Typical Tundra subzone of Yamal Peninsula.

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