Climate Change and Terrestrial Carbon Sequestration in Central Asia

R. Lal, M. Suleimenov, B.A. Stewart, D.O. Hansen & P. Doraiswamy

EDITORS

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Soil and environmental degradation is an important factor that has exacerbated the problem of decline in agronomic production. In addition to a decline in food production, degradation of soil and vegetation also hinders terrestrial ecosystems a net source of atmospheric CO_2 and other greenhouse gases (e.g. N_2O, CH_4). Depletion of the terrestrial C pool (C in soils and biota) has a positive feedback leading to a decline in net primary productivity with attendant reduction in soils and biotic pools.

This 34-chapter volume is a state-of-the-knowledge compendium on terrestrial C sequestration in Central Asia. It is sub-divided into 8 thematic sections:

Section A deals with the biophysical environments of the region.

Section B deals with the water resources of Central Asia.

Section C discusses existing challenges to sustainable agriculture, problems of soil degradation, and the effects of irrigation schemes on secondary salinization.

Section D addresses the principal theme of the book, namely, "soil management and its relationship to carbon dynamics".

Section E describes the important relationship between forest management and carbon dynamics.

Section F presents economic analyses of land use practices.

Materials found in **Section G** deal with important methodological issues regarding the use of GIS, remote sensing, carbon budgeting and scaling.

Section H reviews the knowledge gaps on carbon and climate change and related researchable priorities are recommended.

The book is a principal reference source on soil, water, vegetation, climate, and land use and management in the region. The information presented is of interest to soil scientists, agronomists, foresters, ecologists, hydrologists, climatologists, economists and those interested in policy issues for sustainable management of natural resources. Thematic issues related to carbon sequestration in soils and trees are discussed with reference to their potential to off-set emissions, mitigate climate change, and trade C credits.

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CHAPTER 33

Western Siberian peatlands: Indicators of climate change and their role in global carbon balance

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1 INTRODUCTION

The United Nations Millennium Declaration expresses the intention "to make every effort to ensure the entry into force of the Kyoto Protocol … and to embark on the required reduction in emissions of greenhouse gases." To implement the Millennium Declaration the UN indicated that it would be necessary to reverse the loss of environmental resources. In this context, it emphasized that carbon dioxide emissions are the largest source of the greenhouse gas effect.

Global warming is a major environmental issue and is expected to be greatest at high latitudes. Arctic and sub-arctic landscapes are particularly sensitive to temperature change because of permafrost thawing (Callaghan and Jonasson, 1995). Some areas of the arctic have already experienced warming of up to 0.75°C per decade. The vast region of Siberia is one of them and some have noted that the observed warming over the last 50 years is probably the result of increased greenhouse gas concentrations (Dlugokencky et al., 1998; IPCC, 2001).

Asian Russia has been estimated as a big terrestrial sink of 0.58 Gt atmospheric carbon per year (Kudeyarov, 2004; Zavarzin and Kudeyarov, 2006). However, the precise functional role of pristine peatlands in the global and regional carbon cycle has not yet been evaluated. In particular carbon exchanges in sub-arctic peatlands, such as the lightly vulnerable ones that are prevalent in Western Siberia, have not been adequately researched. It is very important to study them in depth in order to assess the reaction of peatlands to future climate change.

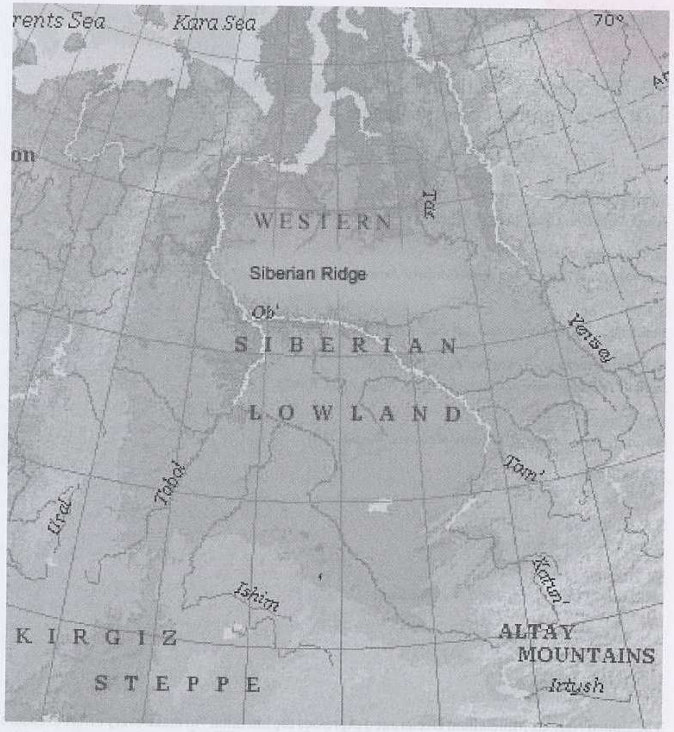


Figure 1. Map of Western Siberian Lowland.

2 PHYSIOGRAPHIC FEATURES OF THE REGION

The Western Siberian plain extends from the Ural Mountains in the west to the central Siberian plateau in the east. The South to North extension is almost 2500 km. A clear landscape sequence of bioclimatic zones has developed on the low, flat relief of the area – from southern steppes to northern tundra. This surface area is about 3 M(million) km^2 in area. Of this total, peatland fens and bogs have been estimated to make up a little more than 1 M km^2 (Vaganov et al., 2005).

The Western Siberian region is divided into two parts by the Siberian Ridge (*Sibirskie uvaly*) which extends in an east-west direction (See Figure 1). The southern part of the Western Siberian Plain is characterized by bioclimatic sub-zones, such as taiga and sub-taiga, forest steppes and steppes with different types of mires. Permafrost reliefs are only present in isolated frozen peat "islands" near slopes of the Siberian Ridge. These small permafrost islands are very unstable and sensitive to climate-driven changes in the landscape (Lapshina and Kirpotin, 2003).

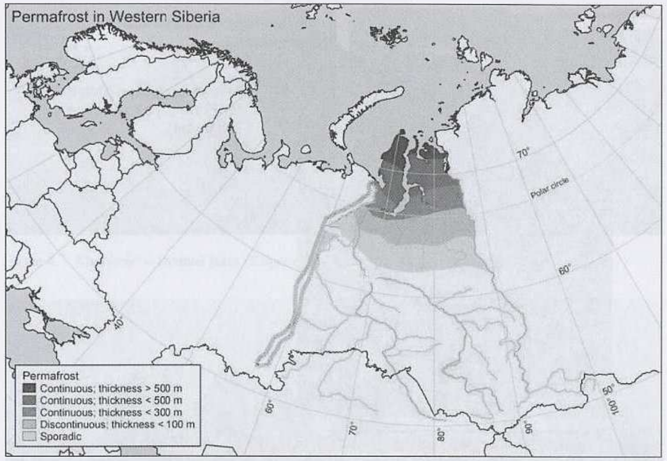


Figure 2. Permafrost distribution in Western Siberia.

North of the Siberian Ridge, the forest-tundra landscapes appear which gradually change into typical tundra in more northern regions. The forest-tundra zone, especially that part found between the Nadym and Pur rivers, is characterised by vast peatlands. The frozen peatlands form flat "palsas" (Matthews et al., 1997). They are found in up to 70% of the surface of the watershed (See Figure 2). Lakes and fens are present over deeper permafrost or where permafrost is absent between the flat *palsas*. Woodlands, open Larch (*Larix sibirica*), and Pine (*Pinus sibirica*) forests cover up to 20% of the total surface. They are found where permafrost is absent, such as on the flood plains, on terraces of large rivers, on narrow strips around some lake shores, and on high mounds between bogs (Kirpotin et al., 1995; Kirpotin et al., 2003).

Contrasting processes are occurring in the southern and northern parts of Western Siberia Bogs are expanding in the southern and middle taiga sub-zones of this region. Bogs in the northern taiga and forest-tundra zones (Kirpotin et al., 2004; Lapshina et al., 2006) are experiencing thermokarst and are being colonized by trees (Kirpotin et al., 1995; Callaghan et al., 1999; Kirpotin, 2003). These processes are probably connected to recent climate changes that have led to global warming.

3 INDICATORS OF CLIMATE CHANGE IN SUB-ARCTIC PEATLANDS

Large areas of arctic and sub-arctic wetlands are very vulnerable to climate change. Changes in them can have an important feedback mechanism in the process of global warming due to their large carbon stocks and the presence of permafrost in them (Gorham, 1991; IPCC, 2001). Extensive mire complexes are present north of latitude N57° in Western Siberia. Shallow permafrost occurs north of latitude N60° and is continuous above the Polar circle. The zone that is most vulnerable to climate change in Western Siberia is about 600 km wide. Large pristine wetlands with discontinuous permafrost are present within this zone. Lapshina et al. (2001) found evidence of climate change in these wetlands, namely, recent peat accumulations on top of partly frozen peat.

Figure 3. Map of landscape patterns for Puritey-Malto site.

Palsa mires are especially sensitive to warming trends due to thawing of frozen peat (Kirpotin et al., 1995; Callaghan et al., 1999; Kirpotin and Vorobiov, 1999; Muldiyarov et al., 2001; Kirpotin et al., 2003; Nelson and Anisimov, 1993; Matthews et al., 1997; Sollid and Sorbel, 1998). Thermokarst features are spreading over extensive areas of the sub-arctic region of Siberia as a consequence.

The authors have made several expeditions to the sub-arctic region of Western Siberia during the past 15 years. They have observed first hand the change dynamics in the landscapes of this region. The flat *palsas* of the Pur-Pe–Tanlova interfluves (64°–65° NL, 75°–76° EL) from 1989 to 1991 were studied in the field. These analyses were supported with aerial photographs (Scale 1: 10 000 and 1: 25 000) (See Figure 3). Cyclic successions in the development of the *palsa* complexes in this region were described in detail. These analyses showed that landscape units experience continuous transformation from one type into other ones (Kirpotin et al., 1995; Kirpotin et al., 2003).

The permafrost, which is 60–100 meters thick, is almost continually distributed here with the only exception being the valleys of large rivers. Thawing of the upper part of the permafrost was observed in the flood-plains of small rivers, on the higher mineral soils under ridge-hollow complex bogs, under the thermokarst lakes, and in thawed *palsa* hollows.

The area between the Nadym and Pur rivers is flat lowland of marine and lacustrine-alluvial genesis and with a prevalence of sandy, loamy soils. Although many rivulets and brooks exist in it, drainage is hampered by its low relief and a subsurface that consists of impervious, frosted soil layers. The presence of many drained thermokarst lakes (these are dry lake basins and are called "Khasyrei" in Russian) has been interpreted by Zemtsov (1976) as indicative of an active neotectonic rise of this area. Khasyrei occupy 20% of the total lake area in the center of the watershed as shown in Figure 4.

Another powerful relief-maker factor that influences the process of swamp development in the sub-arctic conditions is the presence of continuous strong northerly winds. Winds have caused coastal abrasions of the thermokarst lakes as well as their shallowing and swamping from the southern lee side. This process has been facilitated by the accumulation of peat materials in these areas that have been washed away by waves (See Figure 5).

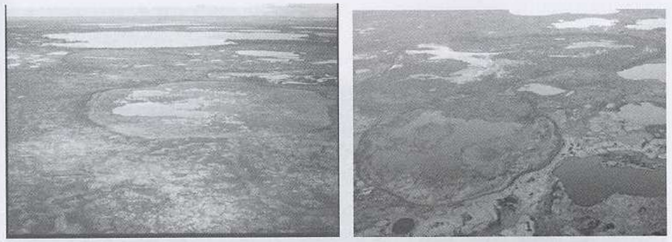
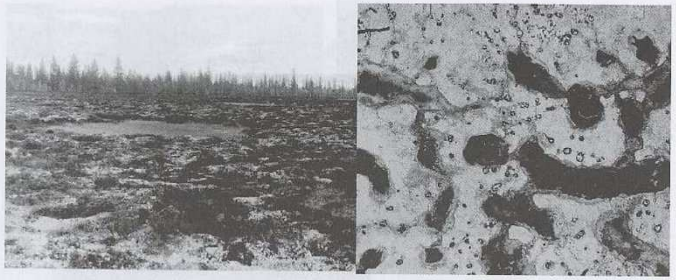


Figure 4. Khasyreis" – Drained lakes (Kirpotin, 1999, 2004).

Figure 5. Coastal abrasion of the thermokarst lake with shallows and swamps on the Southern Lee Side.

4 CURRENT DEVELOPMENT OF PALSAS

Based on their own research, Scandinavian scientists have suggested that flat *palsas* undergo cyclic development. This perspective is based on detailed long-term observations of these *palsas* and has been substantiated with photographic data on the individual stages of this cycle (Matthews et al., 1997; Sollid and Sorbel, 1998). Scandinavian scientists only put forward the idea of the cyclic development of palsas after careful, long-term observation of the formation of separate frozen mounds and inter-palsas thawed hollows. However, palsas are not common to Scandinavia and these limited observations may not be applicable to other regions where similar palsas exist.



(a) (b)

Figure 6. The first stage of permafrost melting (Thermokarst) on the "Palsa" surface: a – ground view; b – porous surface of palsa (air photo, Kirpotin et al., 2004).

Although a completely different situation exists in the sub-Arctic region of western Siberia, the cyclic succession is shown very clearly over the extensive space occupied by flat palsas. All of the cyclic stages of this process are visible and landscape boundaries precisely reflect their processes of development (Kirpotin et al., 2003). The cross over pattern of succeeding stages khasyrei lake palsas are even recognizable from satellite images.

During the first stage of this process, small (0.5–3 m) saucer-shaped round closed dwarf shrub-sedge-sphagnum thermokarst depressions are formed (See Figure 6a). Thermokarst areas are formed by thawing of the upper part of the permafrost which enlarges the "active layer". This process is supported by relatively warm summer rains. In the aerial photographs such palsas are shown to have a characteristic "porous" surface. The surface appears to have been corroded forming numerous round shaped pits (See Figure 6b).

Cracks in the lichen cover and drying of the underlying peat during rainless periods are conditions that lead to the formation of some thermokarst areas (See Figure 7). Moisture remains in the cracks, and some of them increase in size. They burst when the newly added moisture fast freezes. In such cases the affected areas are large and they develop so quickly that sphagnum mosses and/or sedges do not have sufficient time to settle. Bare soil or attenuated wet peat covered by a thin sheet of *Drepanocladus exannulatus* or *Warnstorphia fluitans* can be observed. Sometimes it is actually submerged below open water. Linear areas provide the basis for the formation of inter-palsa hollows and water-tracks with cotton-grass-sedge-sphagnum and sedge-sphagnum vegetation. The hollows and water tracks provide a system for draining the remaining from melted soil-ice, snow and added precipitation water from the flat palsas.

The frozen peat found in the mounds gradually thaws during the summer season and the moisture formed as a result of its thawing flows to inter-palsa hollows, streams and lakes. Therefore, once initiated, thermokarst areas can increase in size even during relatively dry periods. If the area is not intercepted by a water flow, it will gradually increase in size and will normally turn into a small round shaped thermokarst lake (See Figures 8 and 9).

Lakes beds steadily increase in area due to lake shore erosion that is induced by wind born waves as depicted in Figure 4. Shore materials are transported by compensation currents along the lake bottom to upwind shores where new eutrophic sedge fens can develop as indicated in Figure 5.

Numerous thermokarst lakes are spread over the area. Quite often they appear close to each other. Higher located lakes can change into khasyrei when they are drained by water channels and lower situated lakes eventually fill with water as illustrated in Figure 10. Drainage activity can develop are a result of collapses of permafrost flat palsa areas between lakes or due to groundwater flows below thicker areas in the active layers found above permafrost.

Figure 7. Cracks in the Lichen cover and underlying peat (Kirpotin et al., 2004).

Figure 8. Origin of an initial thermokarst lake during the third stage of permafrost melting (Kirpotin et al., 2004).

Figure 9. A round mature lake during the fourth stage of permafrost degradation (Kirpotin et al., 2004).

In summary, during the first stage of the cyclic degradation of flat palsa complexes, thermokarst lakes may appear as a result of the appearance of different sized hollows. These lakes can increase in size due to shore erosion since lake water acts as a heat source which induces further thawing of permafrost layers. These thermkarst lakes can also turn into a khasyrei.

Cotton-grass-sedge-sphagnum swamps develop on the sandy or peat bottoms of drained lake basins. Their khasyrei floors are one to three meters lower than the surrounding flat palsas and are therefore susceptible to late summer frost cause by inflows of cold air. Ice lenses can develop at low, moist places in the mineral or peat soil by such cooling process in periods before a permanent snow cover is formed. The presence of permafrost below the khasyrei floor may enhance this new permafrost formation. The new ice lenses may grow and push up the soil above them. This results in the formation of small two to five meter tall dome-shaped mounds of rounded or oval form. Lichens and dwarf shrubs typically associated with palsa settle on the surface of these small mounds as illustrated in Figures 11 and 12. This process is verified by the presence of a thin layer of sedge-moss peat typically found on *khasyrei* floors, but not on dry tops of mounds formed by ice-heaving. The dry tops of new mounds allow for the settlement of birch shrubs (*Betula nana*) and even of birch trees (*Betula pubescens*). Two to ten year old birch trees have been found which substantiates the presence of ice-heaving activity.

As the heaving by renewed permafrost goes on, the isolated small mounds merge into a uniform system and, depending on the capacity of the peat deposit, they turn into typical flat palsa plateaus as shown in Figure 13. Edges of the drained lake basin can still be seen in aerial photographs at this stage of the cycle.

In summary, it appears that there is a steady cycling of cryogenic processes. The thermokarst and permafrost heaving have been peculiar to Western-Siberia's sub-arctic region for a long time.

When these processes were studied in the early 1990s, it seemed that thermokarst was starting to prevail over new permafrost heaving. However, changes in the sub-arctic region still did not have a dominant character then and it was difficult to say with full confidence where the cryogenic

Figure 10. "Khasyrei" drained lake which lost water to another reservoir or river as fifth stage of permafrost degradation (Kirpotin et al., 2004).

Figure 11. A mature *Khasyrei* with regenerated frozen peat mounds (aerial photo, 1989).

pendulum would swing. Nevertheless, the prevailing view was put forward at that time (Kirpotin et al., 2003), namely, that in the near future the landscape could change significantly if the surface of flat mounds and palsa plateaus covered with lichens were to be steadily reduced in area and giving way to inter-palsa hollows.

During August, 2004 expeditions to New-Urengoy and Pangody (N 66° E 74°) were organized by the EU-INTAS project to study "The effect of climate change on the pristine peatland ecosystems and (sub) actual carbon balance of the permafrost boundary zone in sub-arctic western Siberia." This field research facilitated comparisons with earlier findings. Findings from this research suggested that the thermokarst has indeed expanded and that it now dominates the area being studied. As observed through aerial photographs, the white surfaces, typical for flat palsas covered with whitish

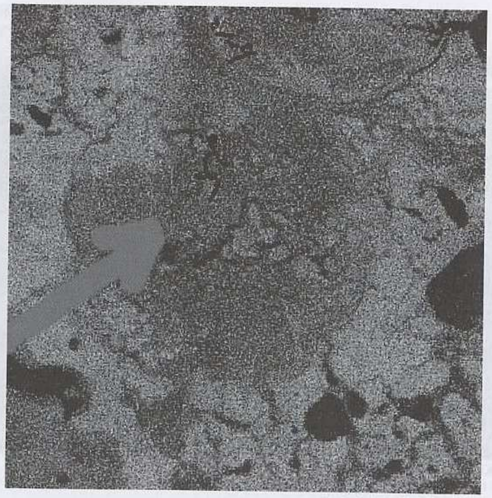


Figure 12. Mature *Khasyrei* with regenerated frozen peat mounds viewed from the ground (Kirpotin et al., 2004).

Figure 13. Old "Khasyrei' with restored plateau mounds in final stage of the "Palsa" development cycle (aerial photo, 1989).

Figure 14. Fresh thermokarst area with drowned dwarf shrubs (Kirpotin et al., 2004).

lichens, decreased in area while green or brown colored hollows increased in area. Thermokarst depressions on the surface of flat palsa develop so swiftly that lichens and dwarf shrubs drawned (Figure 14), and sphagnum mosses in most cases have not had time to settle in them, or are only starting to occupy these fresh water-bearing sites (Figure 15).

Shores of the big thermokarst lakes are one kilometre or more in diameter and are evidently retreating (See Figure 16). However it was not possible to determine the rate of shore retreat by comparing LANDSAT images of 1987 with those of 2002. This suggests that the growth of thermokarst lakes could not have been more than 30 meters over this period. It may be that the rates of shore retreat and thawing of permafrost are even more recent developments caused by warming trends.

Small and middle-sized lakes have also appreciably increased in area as shown in Figure 17. The strip of freshly-submerged dwarf shrubs that are from one to three meters in width – primarily *Ledum palustre* and *Betula rotundifolia* – is clearly visible on the shores of these lakes. The presence of dwarf shrubs leads to the conclusion that these changes are recent, having occurred during the last 3–4 years. Most of the dwarf shrubs still have not had time to decompose.

These data agree with the latest observations of degradation of Arctic sea ice. "Arctic specialists at the US National Snow and Ice Data Centre at Colorado University, who have documented the gradual loss of polar sea ice since 1978, believe that a more dramatic melt began about four years ago…" (Connor, 2005).

The peat is thicker at the Puritey/Malto Key Site (N 64° 40–45′, E 75°24–29′) than at the Northern Key Sit. Prior to undertaking another expedition to it during summer, 2005, we expected to find that frozen bogs – flat palsas – would be more sensitive to climactic warming at the southern edge of the permafrost area than at that further north. However, we found the opposite to be true. The southern palsas were more stable than northern palsas. The changes that we observed at the New Urengoy-Pangody Key Site in 2004 are much greater than those we observed in 2005 at this site. Apparently, this is explained by the level of thermokarst activity, which depends directly on the thickness of the peat layer of palsas. The thick layer of frozen peat protected the palsas at the southern site and did not allow for deep melting. In contrast, as one moves further north, the annual growth of mosses becomes progressively less and the peat layer of palsas becomes correspondingly

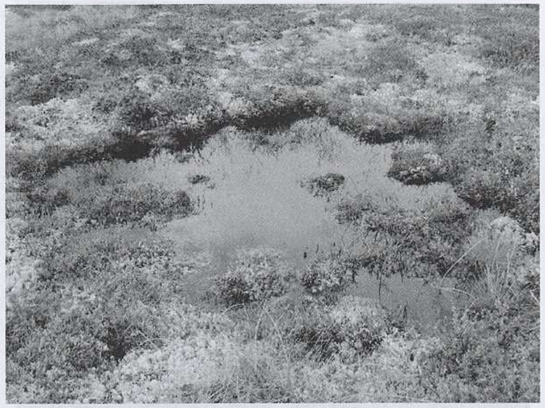


Figure 15. Sphagnum mosses occupy the thermokarst area (Kirpotin, 2004).

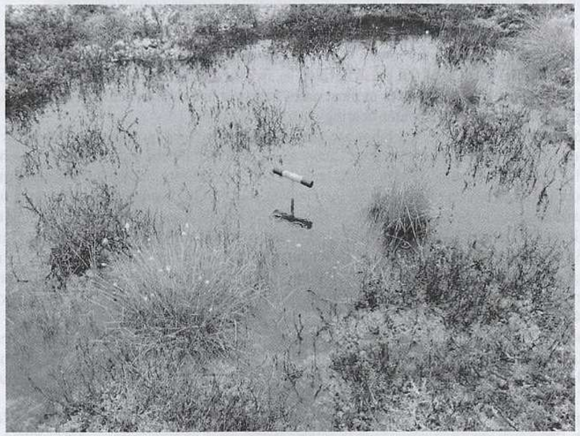


Figure 16. Shore of big lake with diameter greater than one kilometer (Kirpotin et al., 2004).

thinner. The thinner layer of peat melts more easily in the summer, leading to thermokarst in the more northern areas. Thus, very active thermokarst is apparent in areas where the peat layer of the frozen bogs is thin – about 20–30 cm and 50 cm maximum – and it is almost absent on the southern edge of the permafrost zone where the thickness of frozen peat varies from 1.5–2 m (Figure 18). Thus our rough estimate of the area of active thermokarst activity within the West-Siberian Plain is located between 65°–68° latitude N.

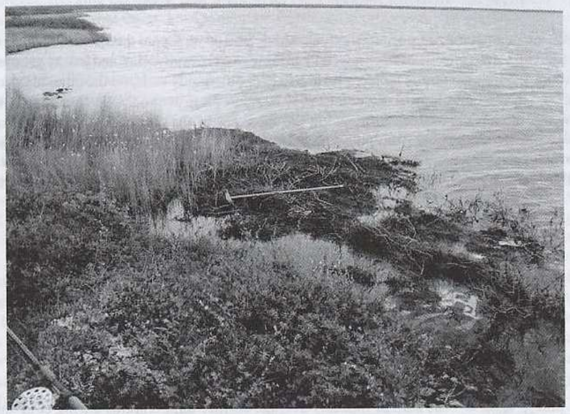


Figure 17. Shore of small lake of about one hundred meters in diameter (Kirpotin et al., 2004).

Figure 18. Graphic description of key sites.

Data from the 2004 and 2005 expeditions are still being processed. Thus, it is not yet possible to quantify the scale, pattern sizes and speed of the thermokarst processes which were observed. However preliminary observations suggest a recent increase in thawing of thermokarst. If so, it may be the start of an irreversible change in the thermokarst landscape of the sub-arctic regions of Western Siberia.

5 MATHEMATICAL MODELLING OF CRYOGENIC PROCESSES

Flat palsas are characterized by ice formations which tend to segregate them. These peat bogs have peat layers with various levels of thickness and are spread over sandy, clay and loamy grounds. Clay soils have the potential to totally collapse up to 6 m in depth. Sandy soils, on the other hand, collapse less than 0.5 m (Geocryological Forecast, 1983). According to processes to estimate freezing and thawing, the basic variables influencing the intensity of their presence on peat grounds are (1) heat conductivity, (2) heat from phase transitions, and (3) thermal resistance to isolation from snow cover, vegetation, etc. Features of permafrost degradation are illustrated by the application of equations to estimate freezing and thawing that were developed by Gosstroy (Recommendations …, 1988).

Freezing and thawing depths are described respectively by the following equations:

$$H_{freez} = 1,2\left(\sqrt{\left(2\lambda_{fr}\sum t^{*}_{fr}720{*}3,6/Q_{phas} + R^{2}_{win}\lambda^{2}_{fr}\right)} - R_{win}\lambda_{fr}\right)$$

$$H_{taw} = \sqrt{\left(2\lambda_{warm}\sum t^{*}_{warm}720{*}3,6/Q_{phas} + R^{2}_{summer}\lambda^{2}_{warm}\right)} - R_{summer}\lambda_{warm}$$

where λ_{fr} and λ_{warm} = the heat conductivity of frozen and thawed ground;
$\sum t_{fr}$ and $\sum t_{warm}$ = –the sum of monthly average surface temperatures during cold and warm periods;
Q_{phas} = the heat of phase transitions;
R_{win} and R_{summer} = the total thermal resistance of isolation; and
$R = h/\lambda$, h = the thickness of isolation from snow, peat, etc.

These equations indicate that the basic condition of permafrost existence is the excess of freezing depth over thawing depth. Analyses of data from these equations allow for the determination of some of the main soil properties that influence freezing and thawing processes. The most essential factors are soil humidity, peat layer thickness, and snow cover thickness. The presence of permafrost in soils depends on thickness of organic horizons, thickness of peat layers and thickness of a snow covers at constant mid-annual temperature and humidity levels.

Figure 19 illustrates the dynamics of freezing and thawing of peat lands according to the given equations and using air temperature, humidity soil humidity and now cover thickness data from the Tarko-Sale meteorological station.

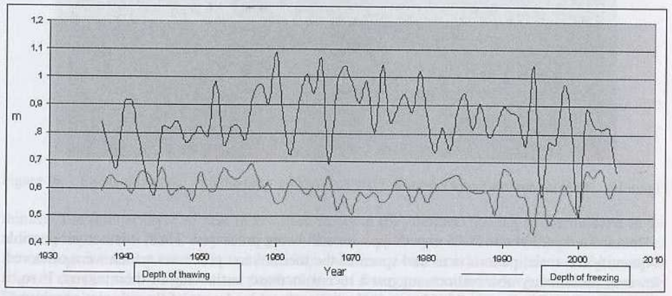


Figure 19. Changes in freezing and thawing depths of peat grounds.

In general, freezing depths of peat are greater than thawing depths in high latitudes. However, climatic conditions, that favor development of thermokarst processes, can appear at any time.

Data analyses using the freezing-thawing equations suggest that intensification of thermokarst processes can be caused by heterogeneity of microclimatic conditions and change processes related to one another. For example, increases in the depth of seasonal thawing and the formation of thermokarst areas are made possible by reductions in or damage to the mosses-lichen layer caused by fire, etc. Although sub-arctic ecosystems allow for restoration of minor damage resulting from bogging processes and peat accumulation, the development of thermokarst is more probable when thermokarst areas are constantly fed by moisture as shown in Figures 20 and 21. The depth of thawing increases as a result of snow accumulation thermokarst craters. Thickness of snow cover is one of major factors that influence freezing and thawing processes in regions that have been studied.

Theory related to cryogenic processes suggests that sites with a low-thickness of peat deposit are the most vulnerable to thermokarst activity because thawing of adjoining grounds will result in greater deformations. It is connected to a high level of ice content and potential collapse of substratum grounds as well as to the greater heat conductivity of mineral grounds compared to peat. Thick layers of peat act as thermo-insulation and keep underlying grounds from thawing.

This feature explains the rather unusual phenomenon observed at the Puritey-Malto key site in 2005 which was described in the previous section. Active thermokarst is apparent in areas where the peat layer of the frozen bogs is less than 50 cm. It is almost absent on the southern edge of the permafrost zone where the thickness of frozen peat varies from 1.5–2 m.

Changes in hydrological conditions can activate permafrost heaving processes. The application of quantitative methods in forecasting the cryogenic heaving processes of freezing peat is rather difficult because researchers have generally focused on studying mineral grounds. Use of developed methods to forecast cryogenic processes of freezing peat is very difficult because no experimental values for hydraulic conductivity of peat exist for unfrozen conditions once thawing has occurred. Furthermore, design procedures are based on characteristics of mineral grounds, such as plasticity and lamination limit, which do not apply to peat. Finally, no consensus exists regarding processes of heaving and segregation related to ice formation. Most scientists recognize heaving, but consider it to be insignificant in the process of segregation of ice formations (Vtjurin and Vtjurina, 1980; Ershov, 1982).

Locations of frost mounds in river valleys, at the bottoms of drained lakes – khasyreis – and at the mouths of brooks is evidence of the important role of moisture in their formation. It is obvious, that

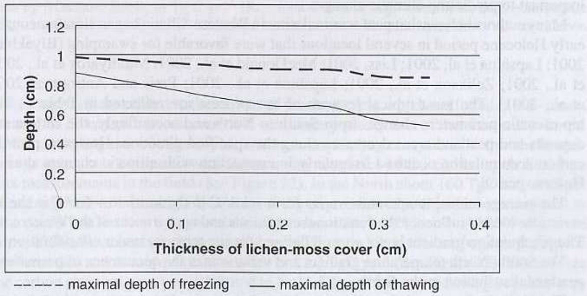


Figure 20. Dependence of the maximal depths of freezing and thawing at different thickness of lichen-moss layer.

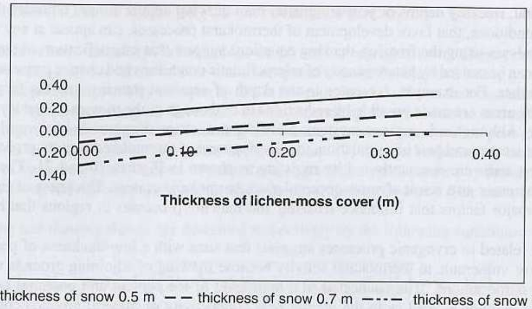


Figure 21. Dependence of a difference of depth of the freezing-thawing border of peat grounds at thickness of snow cover and lichen-moss layer.

palsa mound formation processes are connected to spatial variations in freezing-thawing processes which occur because of variations in vegetation and ground moisture. The general tendency of heaving is probably connected to increases in freezing which are in turn related to increase in moisture supply (Grechischev et al., 1980).

6 WESTERN-SIBERIAN PEATLANDS AND THE GLOBAL CARBON CYCLE

Previous discussion highlights the highly,sensitive and dynamics processes of change in occurring in northern bog landscapes. For this reason, it is important to analyze probable future changes in the carbon cycle and their impact on peatlands, particularly those north of the Sibirsky Uvala ridge in Western Siberia. There is no clear evidence that the area is either a net sink or source of emission into the atmosphere. Furthermore, no data exist on extremely high gas fluxes of carbon dioxide or methane that result from the thawing of pristine northern bogs. Thus, analyses of stabilization mechanisms related to the carbon cycle and carbon balance of peatlands of Western-Siberia are important to predicting climatic changes.

Many authors believe that peat accumulation in Western Siberia began simultaneously during the early Holocene period in several locations that were favorable for swamping (Blyakharchuk et al., 2001; Lapshina et al, 2001; Liss, 2001; MacDonald et al., 2001; Muldiyarov et al., 2001; Velichko et al., 2001; Zelikson et al., 2001; Lapshina et al., 2001; Preis and Antropova, 2001; Turunen et al., 2001). The most typical features of this process are reflected in Table 1. The principal bio-climatic parameters change, from South to North and accordingly, the carbon stock in peat deposits and peatland areas decreases along the specified direction. However, peat deposits and carbon accumulation occurred irregularly in connection with climatic changes during the entire Holcene period.

The average annual temperature varies from −1.1°C in the south to −6.6°C in the north. These variations clearly influence the functional conditions and appearances of the Western Siberia bogs. The precipitation gradient is not so well defined for the territory under consideration.

The South–North temperature gradient and variations in the occurrence of permafrost may limit peatland distribution in the North.

The biological productivity of bogs and fens is in general agreement with variations along the South to North gradient. No significant differences among net primary production values (NPP) of the middle and northern taiga bog ecosystems have been revealed. Wide ranges of NPP have

Table 1. Climatic and carbon accumulation features of bio-geographical sub-zones in western Siberia.

Parameter	Forest tundra	Northern taiga	Middle taiga	Southern taiga
Mean annual temperature, °C	−6.6	−5.3	−3.1	−1.1
Precipitation, mm	400–430	410–500	500–550	450–500
Peatlands area, 10^3 km^2 [1]	108	226	254	316
Peat accumulation in Holocene, mm C yr^{-1} [2,3,4,5]	0.2	0.1–0.3	0.3–0.8	0.8–1.4
Carbon accumulation rate in Holocene, g C m^{-2} yr^{-1} [3,4,5]	n.d.	7–11	12–35	25–60
Peat carbon stock, Pg C [1]	1.9	10.2	15.5	24.2
Net primary production, g dry phytomass, m^{-2} yr^{-1} (min-max) average [6,7]	(300–600)/462	(350–960)/608	(500–890)/570	(240–2400)/813

Note: [1] Yefremov and Yefemova, 2001; [2] Liss, 2001; [3] Lapshina and Polgova, 2001; [4] Bleuten and Lapshina, 2001; [5] Turunen et al., 2001; [6] Kosykh et al., 2003; [7] Kosykh, Mironycheva-Tokareva, 2005; n.d., no data.

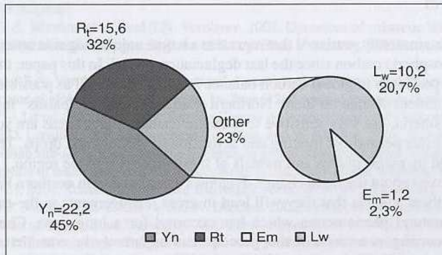


Figure 22. Quantity proportions between carbon cycle components of oligotrophic and mesotrophic mires of West Siberia by (Naumov, 2004), in Tg C yr^{-1} (R_t – total C loss through autotrophic and heterotrophic respiration; E_m – methane-C emission; L_w – dissolved carbon output with mire water flow; Y_n – net carbon sequestration).

been established and they are related to the variety of peatland types which are found in sub-zones. Existing estimations do not take into account the net primary production of marshes and swamps.

The total NPP, including that of oligotrophic and mesotrophic bog ecosystems within the boundaries of the taiga zone, was compared with balance characteristics of the carbon cycle based on direct gas flux measurements in the field (See Figure 22). In the North about 160 TgC is fixated per year by peatland vegetation, assuming a C-content of dry phytomass of 0, 45, which corresponds to 18–32% of the net carbon fixation by terrestrial ecosystems of Russia (Nilson et al., 2003; Zavarzin and Kudeyarov, 2006). Total net carbon sequestration by Western-Siberia forest-bogs excluding the contribution of marshes and swamps, is estimated to be 22.2 TgC yr^{-1} (See Figure 22). The average net Holocene carbon accumulation was estimated to be 11.8 Tg yr^{-1} for raised string bogs that represent 68 M ha in Western Siberia (Turunen et al., 2001). This value is apparently underestimated because researched lands were repeatedly impacted by fires. In addition the extrapolation of a data set from the middle taiga to all Western Siberia probably is not valid because of the wide range of climatic variations in the region. However, a consensus exists that present-day sequestration of atmospheric carbon by northern peatlands is higher than it previously was.

Total emissions through autotrophic and heterotrophic respiration make up 32% of net assimilation flux or 49 Tg C yr^{-1}. Methane emissions represent only 2.3% of total emissions or 1.2 Tg C yr^{-1}. Net carbon assimilation is only about 31% of the NPP calculated using direct counts of shoot and root growth. This discrepancy is explained by a conceptual model of the carbon cycle offered recently by Naumov (2004). According to this model more than 60% of NPP is related to internal ecosystem resources. The internal cycle provides rather independent functioning and stability to the mire ecosystem.

Measurements of carbon gas and methane fluxes from the surface of frozen and thawing bogs that are situated in a permafrost zone, fail to confirm the assumed large emissions of greenhouse gases into the atmosphere as a result of thermokarst degradation (Naumov, 2001). The optimum temperature for the total respiration of northern peatlands is about 12–13°C and is associated with a narrow temperature range of biota activity. Thus, climate warming will inevitably result in the occurrence of more productive ecosystems across diverse ecological systems which will in turn lead to greater carbon accumulation.

7 CONCLUSIONS

Western Siberia contains many peatlands that represent a largue unique bog sinc on earth. They have been a sinc for atmospheric carbon since the last deglaciation period. In this paper, the contribution of Western Siberia peatlands to global carbon balance is assessed as well as possible influences of climatic and environment change on them. Northern peatlands, such as "palsas" in the sub-arctic region of western Siberia, are very sensitive to climatic change. Large areas are subject to rapid the sequential processes permafrost melting and activation of thermokarst drops. These processes are clearly indicated by maps, photos and models of these processes in the region.

Numerous data exist about the rapid change dynamics associated with northern bog landscapes. However, none of them suggest that they will lead to gross infringements in the carbon balance. Thermokarst is a natural phenomenon which has occurred for a long time. Changes in relief and vegetation, occurring as a result of this process, can apparently be considered as "natural" for northern landscapes, but they are accelerated by human activity. An intermediate stage of this evolution may be characterized by progressive swamping and increases in mire ecosystem productivity. Mires have a unique internal mechanism of carbon balance regulation. Due to their non-saturated cycle, they have the capacity to buffer global warming by reducing carbon gases in the atmosphere.

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Research and Development Priorities