An image-based inventory of the spatial structure of West Siberian wetlands

A Peregon\textsuperscript{1,2}, S Maksyutov\textsuperscript{1} and Y Yamagata\textsuperscript{1}

\textsuperscript{1} Center for Global Environmental Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan
\textsuperscript{2} Institute of Soil Science and Agrochemistry SB RAS, Sovetskaya Street, 18, Novosibirsk, 630099, Russia

E-mail: anna.peregon@nies.go.jp, shamil@nies.go.jp and yamagata@nies.go.jp

Received 27 March 2009
Accepted for publication 4 September 2009
Published 15 October 2009
Online at stacks.iop.org/ERL/4/045014

Abstract
Western Siberia contains the world’s most extensive wetlands. Despite its recognition as a significant global carbon reservoir, the spatial structure and composition of micro-topographical elements in patterned wetlands have never been analyzed in detail. To address this uncertainty, we applied a multi-scale approach to make a general and realistic estimation of land cover in Western Siberia. Our approach was based on using a regional wetland typology map (1:2500000 scale), further refined by satellite image classifications (LANDSAT TM, ETM \textsuperscript{+} in 1:200000 scale) on test areas designated in the boreal region of Western Siberia. In addition, QuickBird imagery was used for evaluation the fraction of area occupied by micro-topographical elements within patterned wetlands. Finally, we estimated the areal fractions of these micro-landscapes composing the vegetation mosaic of 20 classes on the wetland typology map for each climatic region of the study area. The total area of peatlands was calculated at $68.5 \times 10^6$ ha, which is higher than earlier estimates. We found almost equal areal extents of ridge–hollow and ridge–hollow–pool patterned wetlands in almost all climatic regions of Western Siberia; in the northern boreal region, however, the ridge–hollow–pool wetland type became dominant and exceeded the areal extent of ridge–hollow wetlands in a proportion of 80–20\%. Also, the open water fraction increased dramatically in the northern boreal region. The results of this survey can be used in models of ecosystem carbon dynamics and inventory of trace gas fluxes in wetlands.

Keywords: Western Siberia, regional scale inventory, wetland typology map, satellite imagery, patterned wetlands, spatial structure, micro-landscapes

1. Introduction
Western Siberia is a major source of atmospheric methane and a sink of carbon dioxide in northern Eurasia (Smith \textit{et al} 2004). The Western Siberian lowland is an extremely paludified area (Walter 1977, Botch and Masing 1983). Mires cover 50–75\% of its area (Romanova 1967) and contain 40\% of the global peat deposits (Walter 1977). The enormous scale of Siberian wetlands generates large problems in numerical assessment and quantifying the spatial distribution of greenhouse gas emissions, patterns of plant biomass, net primary production, and other components of the carbon cycle in terrestrial ecosystems, since a general classification of boreal and sub-arctic wetlands suitable for wall-to-wall land cover analysis does not exist to date.

Existing global maps of wetland typology, CO\textsubscript{2} and CH\textsubscript{4} emissions, and NPP (e.g. Matthews and Fung 1987, Aselmann and Crutzen 1989) contain only a few wetland types over the region of Western Siberia. This information provides global models with a generally realistic estimate of current land cover with coarse spatial resolution.

A proper basis for modeling the carbon cycle at a regional scale has not been elaborated. Earlier estimates of the wetland area of the former Soviet Union (FSU) and Western Siberia...
were reported by Botch et al. (1995), Kivinen and Pakarinen (1981), Tyuremnov (1976), who had based their studies on data from official statistics (the Peat Fund of the USSR) and consider mostly commercial peatlands. New estimates of wetland area using a GIS and inventory of multiple data sources were published by Sheng et al. (2004), although the patterned wetlands were not explicitly analyzed in that study.

On the other hand, all in situ measurements of the major components of the carbon cycle are usually accomplished at fine spatial resolution and comprise a range of wetland micro-landscapes. The presence of topography, with such features as hummocks, hollows, ridges and open water pools, has a profound effect on plant species distribution and productivity (Andrus et al. 1983, Moore et al. 2002, Peregon et al. 2008). Spatial differences in these microsite characteristics (i.e. hydrologic and thermal regimes, nutrient availability) are often as large within an individual wetland as between different wetlands within the same climatic region. Similar patterns were found in the spatial distribution of greenhouse gas fluxes in landplane micro-landscapes (Panikov et al. 1995, Waddington and Roulet 2000, Naumov 2004) and aquatic ecosystems, i.e. wetland lakes and pools in patterned wetlands (Repo et al. 2007, Juutinen et al. 2008). In particular, little is known about wetland lakes as a source of atmospheric carbon. It is estimated that $513 \times 10^{12}$ g of CO$_2$ (Cole et al 1994) and $8-8 \times 10^{12}$ g of CH$_4$ (Bastviken et al. 2004) are released annually from the world’s lakes. Thus, lakes should be taken into account in the regional carbon budget in landscapes like the boreal region of Western Siberia.

2. Materials and methods

Western Siberia is defined as the area between the Ural Mountains and the Yenisey River, and is bounded by the Arctic Ocean to the north. The current study covers the area up to the southern edge of the forested steppe zone. The wetland structure has been estimated at a representative set of locations along a wide north–south climate (i.e. latitudinal) gradient of Western Siberia, as shown in figure 1. Two test sites were designated in the northern boreal region, corresponding to sporadic (D) and continuous permafrost (E) over the area.

As a first step, we produced a regional scale inventory of the wetland area by digitizing a paper-based ‘wetland typology map’ at a 1:2500 000 scale (Romanova et al. 1977), in which the whole of Western Siberia is divided into 20 wetland types and complexes. Geometric correction and digitization of this map were done with MapInfo 8.0 software using the topographic map of the Russian Federation (at a scale of 1:100 000) for georeferencing. Obviously the procedure is prone to error due to the use of hardcopy products and digitization, although the planimetric errors typically appeared to be at most 1.5–2 km.

The wetland typology map was further refined by manual classifications based on satellite imagery to provide more detail on the spatial structure of the patterned wetlands, which are widely distributed in the boreal region of Western Siberia. Therefore, compiling a regional inventory is necessary to scale up the field survey data in order to represent an average value for a particular wetland site.

The purpose of this study was to find a reasonable basis for spatial extrapolation of existing ‘point-scale’ land-survey data. The objectives of this study were: (i) to develop a detailed inventory of wetland area, and (ii) to provide a numerical assessment of the spatial structure of patterned wetlands in the boreal region of Western Siberia.

Figure 1. Study area (gray-colored) and location of the test sites (shaded areas).
Table 1. The wetland area within the bioclimatic subzones of WS (based on the wetland typology map, 1:2.5 million scale).

| Bioclimatic division          | Subzone area (10^6 ha) | Wetland area (10^6 ha) | Percentage of subzone area |
|------------------------------|------------------------|------------------------|-----------------------------|
| Northern tundra              | 24.0                   | 1.6                    | 6.7                         |
| Southern tundra              | 30.5                   | 5.5                    | 18.0                        |
| Forest tundra                | 13.7                   | 3.8                    | 27.7                        |
| Northern taiga               | 58.2                   | 17.8                   | 30.6                        |
| Middle taiga                 | 56.5                   | 19.5                   | 34.5                        |
| Southern taiga               | 42.8                   | 14.2                   | 33.2                        |
| Sub-taiga                    | 27.6                   | 3.6                    | 13.0                        |
| Forest steppe and steppe     | 27.3                   | 2.5                    | 9.2                         |
| Total                        | 280.6                  | 68.5                   | 24.4                        |

Only false-color satellite imagery in digital format composed of near-infrared (NIR) and visible red and green spectral bands (bands 4, 3 and 2) were used in our study. Images were interpreted from a computer monitor for color, tone and texture. The ground survey data (namely visual evaluations and geobotanical descriptions coupled with GPS-based georeferencing) made by local experts during extension field campaigns were used to create the training data set, verification and validation of the classification results. The classification accuracy was estimated at a rate of approximately 100 m because of blurred boundaries between different vegetation classes. About 30 classes of upland forest, wet forest and wetland ecosystems were derived for the boreal region. At this scale, the areas of the test sites were classified into 10 wetland classes, compared with the large-scale wetland typology map, which used only three classes within the boreal region. However, there are also elements of a composite nature presented in this improved classification, such as open patterned wetlands (raised string bogs), that differ in the area fraction occupied by ridges, hollows and small lakes.

Finally, the fractional area coverage of each micro-topographical element making up the vegetation mosaic in patterned wetlands was estimated by interpreting the high resolution satellite imagery (QuickBird, 0.6 m/pixel). We produced a set of 10–12 test plots (0.25–0.35 km²) per classified LANDSAT scene, where the total area of each micro-landscape, average fraction and their standard deviations were calculated automatically in the GIS system. Then this information was applied to elucidate the structure of patterned wetlands on satellite image-based maps for the same climatic (or geographical) region.

3. Results and discussion

The total area of Western Siberia was estimated at about 280 x 10^6 ha. Vast areas are covered by wetlands. Their relative area is minor in the northern tundra and in the steppe, reaching a maximum in the boreal (taiga) region (table 1 and figure 2).

We calculated the total area of Western Siberian peatlands at 68.5 x 10^6 ha, which is a little higher than previous estimates. One reason is that our estimate comprises not only open peat-accumulating wetlands but also forested and grass-dominated wetlands with/or without peat deposits. In fact, wetlands in Russia have been studied for a number of different purposes and from different perspectives (Botch et al 1995). For instance, there are a number of estimates of the wetland area of Western Siberia which report substantially different areas ranging from 32.5 to 59.2 x 10^6 ha made by Neustadt (1971) and Sheng et al (2004), respectively. The estimate by Vompersky et al (1999) based on the soil map at a scale of 1:2.5 million is 58.3 x 10^6 ha. There are many reasons for this diversity—various definitions of wetlands as a land cover class, incompatible boundaries of the region, different approaches to classifications and different evaluation methodologies. Overall, it is generally agreed that the total extent of wetlands in Western Siberia was previously underestimated, largely due to a lack of data in remote regions. For instance, the Wetland typology map based on Russian data surveys does not consider wetlands with shallow (<50 cm) peat deposits. We assume, therefore, that the wetland area could also be underestimated in our study.
### Table 2. Areal fractions of landscape and micro-landscape elements by wetland type.

| Wetland type                        | Areal extent (10⁶ ha) | Elevated Area fraction of micro-landscapes | Depressed |
|-------------------------------------|-----------------------|------------------------------------------|-----------|
|                                     |                       | Hillocks, rollers | Ridges and ryams | Hollows | Eutrophic mires | Lakes (10⁶ ha) | Forest spots |
| Tundra and forest tundra:           |                       |                            |                   |         |                |              |             |
| 1                                   | 4.0                   | 1.0                        | —                 | 0.2     | 2.8             | —             | —           |
| 2                                   | 2.0                   | 0.3                        | —                 | —       | 1.7             | —             | —           |
| Northern taiga:                     |                       |                            |                   |         |                |              |             |
| 3                                   | 6.1                   | 2.3                        | —                 | 1.3     | —               | 2.4           | 0.1         |
| 4                                   | 1.5                   | 0.7                        | —                 | 0.8     | —               | 0.05          | 0.03        |
| 5                                   | 1.9                   | 1.9                        | —                 | —       | —               | —             | —           |
| 6                                   | 2.3                   | 0.9                        | —                 | 0.5     | —               | 0.9           | 0.03        |
| 7                                   | 0.7                   | 0.3                        | —                 | 0.4     | —               | 0.02          | 0.01        |
| 8                                   | 4.2                   | —                          | 1.6               | 0.7     | —               | 1.8           | 0.1         |
| 9                                   | 0.4                   | —                          | 0.2               | 0.2     | —               | —             | 0.03        |
| 10                                  | 1.5                   | —                          | 0.6               | 0.2     | —               | 0.7           | —           |
| 11                                  | 3.7                   | —                          | 3.7               | —       | —               | —             | —           |
| 12                                  | 0.1                   | —                          | 0.1               | —       | —               | —             | —           |
| Middle taiga:                       |                       |                            |                   |         |                |              |             |
| 8                                   | 6.1                   | —                          | 2.2               | 2.7     | —               | 1.2           | —           |
| 9                                   | 1.7                   | —                          | 0.7               | 1.0     | —               | —             | —           |
| 10                                  | 1.7                   | —                          | 0.6               | 0.7     | —               | —             | 0.4         |
| 11                                  | 9.1                   | —                          | 9.1               | —       | —               | —             | —           |
| 12                                  | 1.3                   | —                          | 1.3               | —       | —               | —             | —           |
| Southern taiga:                     |                       |                            |                   |         |                |              |             |
| 8                                   | 4.0                   | —                          | 1.9               | 1.6     | —               | 0.5           | —           |
| 9                                   | 0.8                   | —                          | 0.5               | 0.3     | —               | —             | —           |
| 10                                  | 0.9                   | —                          | 0.4               | 0.4     | —               | 0.1           | —           |
| 11                                  | 4.7                   | —                          | 4.7               | —       | —               | —             | —           |
| 12                                  | 0.7                   | —                          | 0.7               | —       | —               | —             | —           |
| 13                                  | 0.5                   | —                          | 0.5               | —       | —               | —             | —           |
| Sub-taiga:                          |                       |                            |                   |         |                |              |             |
| 8                                   | 0.2                   | —                          | 0.05              | 0.1     | —               | 0.05          | —           |
| 9                                   | 0.05                  | —                          | 0.02              | 0.02    | —               | —             | —           |
| 10                                  | 0.05                  | —                          | 0.01              | 0.03    | —               | 0.01          | —           |
| 11                                  | 0.9                   | —                          | 0.9               | —       | —               | —             | —           |
| 12                                  | 0.1                   | —                          | 0.1               | —       | —               | —             | —           |
| 13                                  | 0.3                   | —                          | 0.3               | —       | —               | —             | —           |
| Forested steppe and steppe:         |                       |                            |                   |         |                |              |             |
| 11                                  | 0.1                   | —                          | 0.1               | —       | —               | —             | —           |
| 14                                  | 0.1                   | —                          | 0.01              | —       | 0.1             | —             | —           |
| 15                                  | 1.4                   | —                          | —                 | 1.4     | —               | —             | —           |
| 16                                  | 1.0                   | —                          | —                 | 1.0     | —               | —             | —           |
| 17                                  | 0.3                   | —                          | 0.01              | —       | 0.3             | —             | —           |
| 18                                  | 2.1                   | —                          | —                 | —       | 2.1             | —             | —           |
| 19                                  | 0.1                   | —                          | —                 | 0.1     | —               | —             | —           |
| 20                                  | 1.9                   |                            |                   |         |                |              | —           |
| Total                               | 68.5                  | 7.3                        | 30.2              | 11.2    | 9.5             | 8.1           | 0.3         |

a Wetland types according to Romanova et al (1977). A. Humid zone. I. Oligotrophic and meso-eutrophic lowland polygon mires: 1, polygonal-roller and polygonal-fissure mires; 2, polygonal mires combined with grass- and moss-dominated mires. II. Oligotrophic and mesotrophic flat-palsa mires: 3, patterned (hollow and hollow-pool) flat-palsa bogs; 4, flat-palsa and high-palsa bogs; 5, shrub-dominated tussock mires. III. High-palsa oligo-mesotrophic and oligo-eutrophic mires: 6, high palsa–hollow and pool–hollow patterned mires; 7, high-palsa and flat-palsa mires. IV. Oligotrophic (Sphagnum-dominated) domed bogs: 8, Sphagnum-dominated bogs with pools and open stand of trees; 9, ridge–hollow patterned bogs; 10, ridge–hollow–pool and ridge–pool patterned bogs; 11, forested (treed) shubs- and moss-dominated mires; 12, moss-dominated treed (Pinus) mires. B. Semi-arid zone. V. Eutrophic and mesotrophic (sedge-brown mosses treed) flat mires: 13, ridge–hollow patterned bogs; 14, grass–mossy mires and oligotrophic pine–dwarf shrub–Sphagnum raised bogs—ryams; 15, grass– and grass–moss-dominated mires; 16, grass–sedge and Sphagnum–sedge hardwood swamps. C. Arid zone. VI. Eutrophic reed and grass-dominated salt marches: 17, reed and sedge–reed mires concerning oligotrophic raised bogs (ryam); 18, reed–sedge and grassy mires; 19, grass-dominated mires on salty soils; 20, unidentified mire type.

b For wetland types 1–2 and 14, 19, estimates are based on literature survey.
At the next stage of our analysis, we refined the wetland typology map by dividing the wetland types that were initially integrated into one class in the legend and revised the spatial structure of these heterogeneous wetlands (table 2). We found almost equal proportions between the areal extent of ridge–hollow and ridge–hollow–pool wetlands in middle-, southern and sub-taiga regions of WS.

In the northern boreal region, however, the ridge–hollow–pool wetland type became dominant and exceeded the areal extent of ridge–hollow wetlands in a proportion of 80–20%. The increase in the ridge–hollow–pool type could be associated with an increasing amount of surface water and progressive waterlogging of the boreal region in WS (see Grippa et al. 2007).

The information on the spatial structure of heterogeneous (patterned) wetlands is compiled in table 3 and figure 3. Regarding the spatial structure of ridge–hollow bogs, we found minor variability in the ratio between elevated and depressed micro-landscapes making up the vegetation mosaic; but there was no general trend observed along the designated north–south transect. Namely, the ridges contributed 36–62% and hollows and floating mats from 38 up to 58% of the area regardless of the geographical location of the test site. There were no floating mats in the vegetation mosaic in southern boreal regions (test areas A and B). Their contribution increased northward up to 8% of the area, apparently due to progressive inundation.

Analogously, the contribution of ridges was much less variable in ridge–hollow–pool patterned bogs, although it was always less than that of ridge–hollow bogs. The fraction of hollows typically ranged between 40 and 55%, except in the northern regions (test areas D and E) where it was less. Conversely, the open water fraction (i.e. lakes and pools) increased dramatically in the northern boreal region. The forest spots added only a minor fraction to the wetland structure and were found only in the northern boreal region of Western Siberia.

4. Conclusions

The data presented in this paper represent a substantial advance in our knowledge of the areal extent, distribution and spatial heterogeneity of Western Siberian wetlands. Our results can be used in local-to-regional scale land and atmosphere modeling studies, or in quantifying trace gas fluxes and sinks.
of atmospheric carbon in wetlands. More detailed imagery-based surveys are required to compile adequate land cover data in middle- and fine-scale resolutions for vast areas of Western Siberia.

Acknowledgments

This study is relevant to the northern Eurasia Earth Science Partnership Initiative (NEESPI), aiming to better integrate field data, models and satellite observations to characterize and quantify the effects of climate change in high latitude ecosystems. We thank all members of NEESPI community for their comments and useful recommendations at all stages of our study. This work was supported by the Global Environmental Research Fund of the Ministry of Environment, Japan: Integrated Study for Terrestrial Carbon Management of Asia in the 21st Century based on Scientific Advancement (S-1), Grants-in-aid for Creative Scientific Research (2005/17GS0203) of the Ministry of Education, Science, Sports and Culture, Japan and Research on the Global Forest Carbon Monitoring System (B-081) projects. Also, this study is going under an umbrella of the NASA Land Cover and Land Use Change Program (Changes of Land Cover and Land Use and Greenhouse Gas Emissions in Northern Eurasia: IHAQ project).

References

Andrus R, Wagner D J and Titus J E 1983 Vertical distribution of Sphagnum mosses along hummock-hollow gradients Can. J. Bot. 61 3128–39

Aselmann I and Crutzen P J 1989 Global distribution of natural Andrus R, Wagner D J and Titus J E 1983 Vertical distribution of freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions J. Atmos. Chem. 8 307–58

Bastviken D, Cole J, Pace M and Tranvik L 2004 Methane emissions from lakes: dependence of lake characteristics, two regional assessments, and a global estimate Glob. Biogeochem. Cycles 18 GB4009

Botch M S and Masing V V 1983 Mire ecosystems in the USSR Botch M S and Masing V V 1983 Mire ecosystems in the USSR Mires: Swamp, Bog, Fen and Moor, B. Regional Studies ed A J P Gore (New York: Elsevier Science) pp 95–152

Botch M S, Kobak K, Vinson T S and Kolchugina T P 1995 Carbon pools and accumulation in peatlands of the Former Soviet Union Glob. Biogeochem. Cycles 9 37–46

Cole J J, Caraco N F, Kling G W and Kratz T K 1994 Carbon dioxide supersaturation in the surface waters of lakes Science 265 1569–70

Grippa M, Mognard N M, Le Toan T and Biancamaria S 2007 Observations of changes in surface water over the Western Siberia lowland Geophys. Res. Lett. 34 L15043

Juutinen S, Rantakari M, Kortelainen P, Huttunen J T, Larmola T, Alm J, Silvola J and Martikainen P J 2008 Biogeosci. Discuss. 5 3457–96

Kivinen E and Pakarinen P 1981 Geographical distribution of peat resources and major peatland complex types in the world Ann. Acad. Sci. Fenn. A 132 28

Lapshina E D and Vasiliev S V 2001 Carbon storage and atmospheric exchange by Western Siberian peatlands FGUU Scientific Reports ed W Bleuten and E D Lapshina, Utrecht, Tomsk., Appendix 1: Land Unit Maps

Matthews E and Fung I 1987 Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources Glob. Biogeochem. Cycles I 61–86

Moore T R, Rubier J L, Frolkina S E, Lafluer P M and Routlet N T 2002 Plant biomass and production and CO2 exchange in an oligotrophic bog J. Ecol. 90 25–36

Naumov A V 2004 Carbon budget and emission of greenhouse gases in bog ecosystems of Western Siberia Eurasian Soil Sci. 37 58–64

Neustadt M I 1971 The world natural phenomenon—bogs of the West Siberian lowland Izv. Akad. Nauk SSSR, Ser. Geogr. 21–34 (in Russian)

Panikov N S, Sizova M V, Zeleny V V, Machov G A, Naumov A V and Gazdzhiev I M 1995 Methane and carbon dioxide emission from several Vasyugan wetlands: spatial and temporal flux variations Ecol. Chem. 4 13–23

Peregon A, Maksyutov S, Kosykh N P and Mironycheva-Tokareva N P 2008 Map-based inventory of wetland biomass and near production in Western Siberia J. Geophys. Res. 113 G01007

Repo M E, Huttunen J T, Naumov A V, Chichulin A V, Lapshina E D, Bleuten W and Martikainen P J 2007 Release of CO2 and CH4 from small wetland lakes in Western Siberia Tellus B 59 788–96

Romanova E A 1967 Nekotorye morfologicheskie kharakteristiki oligotrofnykh bolotnykh landshaftov Zapadno-Sibirskoi nizmennosti kak osnova ikh tipologirovaniya Priroda Bolot I Metody Ikh Issledovaniya (Moscow: Nauka) pp 63–7 (in Russian)

Romanova E A, Bybina R T, Golitsyna E F, Ivanova G M, Usova L I and Trushnikova L G 1977 Tipologicheskaya karta bolot Zapadno-Sibirskoi ravnini (Wetland typology map of West Siberian lowland) scale 1:2500 000 GUGK, Leningrad

Sheng Y, Smith L, MacDonald G M, Kremnenski K V, Frey K E, Velichko A A, Lee M, Beilman D W and Dubinin P 2004 A high-resolution GIS-based inventory of the West Siberian peat carbon pool Glob. Biogeochem. Cycles 18 GB3004

Smith L C, MacDonald G M, Velichko A A, Beilman D W, Borisova O K, Frey K E, Kremnenski K V and Sheng Y 2004 Siberian peatlands a net carbon sink and global methane source since the early Holocene Science 303 353–6

Tyuremnov S N 1976 Torfyanye Mestorozdenya (Moscow: Nedra) p 488 (in Russian)

Vompersky S E, Tsyganova O P, Kovalev A G, Glukhova T V and Valyaeva N A 1999 Zabolochennost territorii Rossii kak factor svyazivaniya atmosfernogo ugleroda Global Change of Environment and Climate ed G A Zavarzin (Moscow: Min. of Sci. and Technol. Of the Rus, Fed.) pp 124–45 (in Russian)

Waddington J M and Routlet N T 2000 Carbon balance of a boreal patterned peatland Glob. Change Biol. 6 87–97

Walter H 1977 The oligotrophic peatlands of Western Siberia—the largest peinohelobiome in the world Vegetatio 34 167–78