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Application of the Multi-Scale Remote Sensing and GIS to Mapping Net Primary Production in West Siberian Wetlands

By

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Summary

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The goal of this study is to scale up the all available field survey and literature data to provide wetland net primary production (NPP) inventory map for West Siberia. Field survey data were obtained within Taiga zone for major types of wetland micro-landscapes. In order to compile reginal scale inventory, we have developed multi-scale approach, in which we use regional wetland typology map (1:2.5M scale), further refined by satellite image classifications (Landsat, Spot, Resurs, 1:100 – 1:200K scale). Satellite images for test areas within Taiga Zone of Western Siberia are classified using common classification system (30 wetland classes). For evaluation of area fraction occupied by micro-landscape elements within patterned wetlands we used aerial photography (1:25K scale). As a result, we produced a GIS map-based inventory of ecosystem NPP in Western Siberia wetlands, using observation on all major micro landscape elements and area fraction of those landscape elements estimated for each wetland class on wetland typology map.

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Introduction

The vast areas of boreal and arctic wetlands play a significant role in the global carbon cycle that has recently been discussed by a number of researchers. Although wetlands have been accumulating 20-40 $gC/m^2/yr$ over the last 5.000-10.000 years since deglaciation (GORHAM 1991), they have the potential to become net sources of C to the atmosphere under a warmer and drier climate. Northern peatlands alone, which are defined to be north of 50° N, store approximately 30% (455Pg(=10^{15}g)C) of the total terrestrial pool of soil carbon in undecomposed peat (GORHAM 1991), despite covering only 3% of the earth's land surface ($3.6\times10^6 km^2$) (CLYMO 1987). Carbon dating of peat profiles suggests that the area of northern peatlands is constantly expanded through last 11K years (NEUSTADT 1977, GAJEVSKY & al. 2001).

The build up of CO_2 in atmosphere and global warming have the potential to affect net primary production (NPP) and carbon storage of terrestrial ecosystems and will be more pronounced in northern latitudes. Thus it is important to identify the potential range and spatial distribution of NPP and carbon storage responses to elevated atmospheric CO_2.

Net primary production values on the wetlands vary within the wide range. BARTSCH & MOORE 1985 estimated that NPP was from 50 to 150 $gCm^{-2}yr^{-1}$ in the subarctic region and from 100 to 200 $gCm^{-2}yr^{-1}$ for boreal bogs. Various field studies have shown that the NPP of marches and swamps of Northern American and Europe is in the range from 400 to 1000 $gCm^{-2}yr^{-1}$ (VAN DER VALK & BLISS 1971, BARADZIEJ 1974). The presence of topography (ridges, hummocks, lawns, etc.) has profound effect on the plant species distribution and productivity (e.g. MOORE & al. 2002).

Earlier studies (e.g. SMITH & FORREST 1978, collated in CAMPBELL & al. 2000) have described the distribution of biomass within peatlands, primarily above ground, but there have been few measurements of below-ground biomass and production (FINER & al. 1993, SAARINEN 1996), who have determined root-accocated NPP to be from 25 to 200 $gCm^{-2}yr^{-1}$. Ignoring the below-ground component, which is the usual practice because measurement of root production in peatlands is difficult, excluded well over 50% of the biomass and a large portion of the annual production (MOORE & al. 2002). Recently, NPP estimations have been made for major wetland types in West Siberia (WS) (BAZILEVICH 1993, KOSYKH 2000, VASILIEV & al. 2001, etc.). It is necessary to develop detailed wetland inventories as the base for further research.

Existing (global) inventories of wetland types, CO_2 and CH_4 emissions, and NPP give us only crude representation of the wetland typology for Western Siberia. MATTHEWS & FUNG 1987 grouped the 28 UNESCO wetland vegetation classes into the 5 more general categories of forested bog, nonforested bog, forested swamp, nonforested swamp, and alluvial wetland formations and estimated the global flooded wetlands areas of 5.3×10^{12} m^2. Using different data sources, ASELMANN & CRUTZEN 1989 also examined the global distribution of wetlands emitting CH_4. These authors grouped 45 different vegetation types into 6 general categories. This information provides global models with a generally realistic estimate of current landcover at coarse spatial resolution. However, these databases suffer from lack of consistency in vegetation classification used, variable measurement techniques, and a variety of special sampling resolutions (RUNNING & al. 1995).

The latest estimates of the area, carbon storage and accumulation rate in mires of former Soviet Union (FSU) were reported by BOTCH & al. 1995, where uncertainty also arose from poor accounting of shallow mires that was not represented in Russian peat inventories. The area of peatlands in the FSU may be twice the area reported by KIVINEN & PAKARINEN 1981, TYUREMNOV 1976, etc., who based their estimates on data from the Peat Fund of the USSR which considers mostly commercial peatlands. Peat and carbon content data for peatlands of West Siberia are summarized recently by YEFREMOV & YEFREMOVA 2001, SMITH & al. 2004. Still, we have only limited data available about contemporary wetland vegetation for different parts of large Siberian territory.

The purposes of the present study are (i) to provide improved estimation of the area extent and distribution of the major mire types in the Western Siberia lowland, (ii) determine the spatial variability of NPP and biomass values in relation to macro/micro landscape and position within the bioclimatic division of Siberian territory, (iii) represent of this material in the form of digital vector map at 1:2.5M scale.

Material and Methods

Site description

West Siberian region refers to the area between the Ural Mountains and the Yenisey River. The mires are abundant, and the soils are water-saturated. West Siberia is extremely paludified territory, where mires cover up to 50-75% of the land area, and ~ 40% of the global peat deposits are found there (WALTER 1977).

To obtain reasonable estimates, measurements of the NPP rates are needed at the numerous sites, which cover a range of typical microsites and are situated in different locations along a wide N-S climate gradient, according to latitudinal divisions of WS (Table 1). Test areas for our observations were selected according to this concept in each 3 subzones within Taiga zone in the central part of selected territory.

Table 1. Location of test areas.

Latitudinal division	Location	Precipitation, mm/yr	Average annual temperature, t°C	Permafrost
Southern Taiga	56°-58° N 78-80° S	400-500	-0,6, -1,6	-
Middle Taiga	60°50′ N 76°40′ S	400-600	-2,8, -3,7	-
Northern Taiga	62°58′-63°16′ N 75°11′- 75°29′ S	336-360	-3,4, -5,4	40 cm below the surface

Sampling and research methods

To estimate regional terrestrial ecosystem NPP, two methods are available: (1) extrapolating the local field NPP measurements up to the region, using a vegetation map and (2) modeling plant productivity at regional and grid point scale. Modern vegetation models (WOODWARD 1987, PRENTICE & al. 1992, etc.) are improving the representation of the global distribution of vegetation, but still have to be corrected by observations. Consequently, TOWNSHEND & al. 1991 argued that the more accurate global vegetation classification must be based on remote sensing of actual landcover. The theory and rationale of the use of remote sensing in model-based estimation of photosynthesis and NPP, including also wetlands vegetation, are described in POTTER & al. 1993, RUIMY & al. 1994, etc. But we use here a more simple, inventory-type approach to application of the remote sensing and observation data.

Method 1: Field observation and harvesting procedure

Detailed geobotanical descriptions were made on each test area, where 5-7 (0.5×0.5 m) sampling sites were selected on different micro-topography. Observed total net primary production (NPP) is defined as sum of above-ground (ANP), land-surface and below-ground (BNP) components: NPP=ANP+LNP+BNP;

ANP – measured by harvesting new plant increment after a 1-year period for the vascular plant of each sampling site by clipping of vegetation two/three times during the growing season. Stems, stem bases, rhizomes, roots of herbs and sedges, herbs, shrubs and dwarf shrubs, located below the clipping line, we considered as below-ground biomass, whereas we took the living bryophytes below the clipping line as contributing to land surface biomass. Clipped (raw) material was sorted by species and oven-dried at 108°C. Sphagnum NPP was measured by the cranked wire method (CLYMO 1970) in our modification – "individual tags" method (KOSYKH 1999) which allowed to avoid affecting linear growth of shoots. The tagged plants were sampled the next year.

BNP is conventionally estimated to be 50-80% of NPP based on WALLEN 1992. We have used our own method for extraction of bellow-ground organs, which were formed in present year – BNP, (KOSYKH & al. 2003). On the same sites, where above-ground fraction was clipped, we sampled below-ground biomass in 10-cm increments to 30-40 cm below the mosses surface, i.e. the level of moss capitula. The live below-ground biomass was sorted from the peat and ascribed to shrub or a sedge/herb origin, and weighed after over-drying.

In addition to our own NPP and biomass data we used 91 NPP estimations by other authors, found in scientific literature for boreal and northern mires (KOSYKH 2003b).

Method 2: Remote sensing application

A "fusion method" for different spatial resolutions data has been developed for monitoring the scale different phenomena in this research. We have used a multi-scale approach to mapping NPP based on wetland typology map at 1:2.5M scale (ROMANOVA & al. 1977). There are only 20 wetland types and complexes for total West Siberian territory. Average fractions in vegetation mosaic of those 20 classes were derived from remote sensing and ground survey data.

As a first step, several Landsat/SPOT HRV/Resours satellite images were used to create the landscape classification maps (appr. 1:100 – 1:200K scale) for each selected test area, where about 30 wetland ecosystems supplemented by field observation have been presented for Taiga Zone. On this stage, we have ability to mark out more wetland classes, compared with wetland typology map, where some area represented by just 3 classes, but actually we see more then 10 classes on satellite image classification. As the unified classification system or legend for these maps we used the wetland types classification by LAPSHINA & VASILIEV 2001. But there are also elements of composite nature have been presented in this classification, such as open patterned wetlands, which differ in area fraction occupied by ridges, hollows and small lakes. This kind of wetland type is widely distributed in WS.

Secondly, we evaluate the fractional area coverage of micro-landscape elements (ridges, hollows and lakes) for each type of patterned wetlands by using the aerial photographs (1:25K scale), where available. We applied this information for estimation of patterned wetlands structure on satellite image-based maps within the same bioclimatic zone according to latitudinal division. We had no aerial photographs for Northern Taiga test area, therefore we used ground survey data for estimation of cover ratio of ridges, hollows, hillocks and lakes.

Applying this data on fractional area coverage per each wetland type, we have produced the regional scale NPP map, where field observations are scaled up with different spatial resolution remote sensing data into average value for whole area. The average standard deviation for NPP observations within the same vegetation type was 11% of the value.

Results and Discussion

According to wetland typology map (ROMANOVA & al. 1977), wetlands cover total of $668\times10^9 m^2$ or 26% of total area, with maximum fraction in Taiga zone (about 30%) and minimum in northern Tundra of about 7%. Areas of main 20 wetland types were determined within 3 hydrological zones, subdivided as areas of excessive, intermediate and insufficient water supply (Table 2). Area of excessive water supply includes following geobotanical regions: Tundra and forested Tundra, where the total paludified area is $60\times10^9 m^2$, $550\times10^9 m^2$ of wetlands are situated in Taiga zone. Contribution of intermediate water supply (forest-steppe and subTaiga) area is $33\times10^9 m^2$. Insufficient water supply area (steppes) with eutrophic reed and grassy wetlands has about $25\times10^9 m^2$ of wetland's area.

Table 2. Wetland NPP (left, TgDM/yr) and area (right, 10^6 ha) by microlandscape components

Wetland type*	Total (without woody layer)	Grass-shrubs-mossy layer						Woody layer
		area fraction of micro-landscapes						
		elevated		depressed				
		hillocks, rollers	ridges and ryams	ombrotrophic hollows	mesotrophic hollows	eutrophic hollows	lakes, 10^6 ha,	
				Tundra				
1	29.1/4.0	5.8/1.0	-	0.7/0.2	-	22.6/2.8	-	-
2	15.9/2.0	1.8/0.3	-	-	-	14.1/1.7	-	-
				Northern Taiga				
3	24.2/6.2	15.9/2.8	-	8.3/2.3	-	-	1.1	-
4	7.9/1.5	5.6/0.7	-	2.0/0.6	0.3/0.01	-	0.2	-
5	8.5/1.9	8.5/1.9	-	-	-	-	-	-
6	11.9/2.3	6.2/0.8	1.3/0.2	2.8/0.6	1.6/0.2	-	0.4	-
7	3.7/0.7	2.5/0.3	-	1.1/0.3	0.1/0.01	-	0.1	-
				Middle and Southern Taiga regions				
8	50.4/10.8	-	19.5/2.9	30.9/6.2	-	-	1.7	0.1/0.3
9	32.7/7.0	-	12.7/1,9	20.0/4.0	-	-	1.1	0.3/1.9
10	42.7/3.8		6.0/0.9	3.8/0.8	7.0/0.8	25.9/1.3	-	-
11	123.9/18.5	-	123.9/18.5	-	-	-	-	87.3/18.5
12	14.9/2.2	-	14.9/2.2	-	-	-	-	-
				Forested steppe and steppe				
14	16.1/0.7	-	8.6/0.4	-	-	7.5/0.4	-	-
15	1.5/0.1	-	0.1/0.01	-	-	1.4/0.1	-	0.01/0.008
16	28.9/1.4	-	-	-	-	28.9/1.4	-	-
17	20.7/1.0	-	-	-	-	20.7/1.0	-	6.1/1.0
18	5.1/0.3	-	0.1/0.01	-	-	5.0/0.3	-	0.1/0.03
19	89.8/2.1	-	-	-	-	89.8/2.1	-	-

*next page

20	3.2/0.1	-	-	-	-	3.2/0.1	-	-
21	-/1.9							
Total	530.5/68.7	46.3/7.8	187.0/27.2	69.4/16.3	9.1/0.3	218.7/9.9	5.3	93.9/22.0

*Wetland types according to ROMANOVA & al. 1977.

A. Excessive water supply zone. I. Poligonal ombrotrophic and meso-eutrophic mires: 1 - Polygonal-roller and polygonal-fissure mires, 2 - Polygonal mires combined with grass and grass-mosses. II. Flat-palsa ombrotrophic and mesotrophic mires: 3 - Patterned flat palsa - hollow and flat-palsa-hollow-lake, 4 - Flat palsa and high palsa mires, 5 - Shrubby small-palsa mires. III. High-palsa ombro-mesotrophic and ombro-eutrophic mires: 6 - High palsa-hollow and high palsa-pool-hollow patterned mires, 7 - High palsa and flat palsa complexes. IV. Ombrotrophic (Sphagnum) raised bog: 8 - Mire-big pools (with thin trees), 9-10-Ridge-hollow, ridge-hollow-pool patterned wetlands and ridge-pool mires, 11 - Forested and mossy forested mires, 12 - Moss with pine trees.

B. Intermediate water supply zone. V. Eutrophic and mesotrophic (sedge-brown mosses and forested) flat mires: 14 - Ridge-hollow mires, 15 - Grassy-mosses mires in complex with ombrotrophic raised bogs - ryams, 16 - Grass and grassy-mosses mires, 17 - Birch grassy-sedges, birch Sphagnum-sedges and Pine-birch Sphagnum-sedges forested swamps.

C. Insufficient water supply zone. VI. Eutrophic (reed) and grassy mires with considerable salinity: 18 - Reed, sedge-reed mires in complex with ombrotrophic raised bogs (ryam), 19 - Reed-sedges and grassy mires, 20 - Grassy mires on salted soils, 21-Unidentified mire type.

Most of NPP is created in Taiga zone (320.8 TgDM/yr), with maximum contribution from southern subzone (60%). Other parts contribute less: 21% middle Taiga, and 19% northern Taiga. Most productive are forested wetlands and ridges, their contribution is about 56% in whole Taiga region. 15% of total NPP in Taiga is contributed by mesotrophic and eutrophic hollows, in spite of their minor area fraction, they are productive (35TgDM/yr total). In Tundra region wetland NPP is 45 TgDM/yr, in forested steppe and steppe area NPP is about 165 TgDM/yr.

Adding woody layer increases the total NPP and phytomass values. Of course, the productivity of woody layer varies with density and canopy height, but the total phytomass storage is minor (164 TgDM) and NPP is 93.9 TgDM/yr. Total NPP of West Siberian wetlands is estimated as 530.5 TgDM (teragram/megaton dry matter)yr^{-1}, or 624.4 TgDM/yr when woody parts are included.

We should note finding some higher NPP values to the north of Taiga Zone. There are two possible causes for the difference: the first one is difference in observation method; another reason could be higher total NPP value in northern grasslands compared to ombrotrophic poor mires.

Table 3. Average NPP ($gDM/m^2/yr^{-1}$) by vegetation layer.

Latitudinal division	Average NPP, $gDM/m2/yr^{-1}$	NPP fraction by vegetation layer			Average biomass, gDM/m2
		Above-ground, %	Land-surface (mosses), %	Bellow-ground, %	
North Taiga	354-958	11	38	51	770-2400
Middle Taiga	500-887	13	40	47	970-1748
South Taiga	527-1970	10	28	62	883-3570

West Siberian wetlands have significant NPP due to the high productivity of mosses (up to 40 %) and below-ground fraction of grasses (more than 60% in southern Taiga). NPP of wetlands increases from north to south, in Taiga zone (Table 3). Increase of below-ground NPP fraction and reduction of moss species contribution have been registered in the same direction.

Living biomass storage of wetlands is 10-30% of total biomass storage of upland forest ecosystems in the same bioclimatic zone. On the contrary, NPP value on the wetlands is higher in Tundra, forested Tundra, northern Taiga and especially in southern grassland type wetlands (1.5-2 times larger, compared with phytomass value). NPP of wetlands and forests was found to be similar in middle and southern Taiga subzones.

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