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A high-resolution GIS-based inventory of the west Siberian peat carbon pool

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[1] The West Siberian Lowland (WSL) contains the world's most extensive peatlands and a substantial fraction of the global terrestrial carbon pool. Despite its recognition as a carbon reservoir of great significance, the extent, thickness, and carbon content of WSL peatlands have not been analyzed in detail. This paper compiles a wide array of data into a geographic information system (GIS) to create a high-resolution, spatially explicit digital inventory of all WSL peatlands and their associated physical properties. Detailed measurements for nearly 10,000 individual peatlands (patches) are based on compilation of previously unpublished Russian field and ancillary map data, satellite imagery, previously published depth measurements, and our own field depth and core measurements taken throughout the region during field campaigns in 1999, 2000, and 2001. At the patch level, carbon storage is estimated as the product of peatland area, depth, and carbon content. Estimates of peatland area are validated from RESURS-01 satellite images, and the quality of the Russian peatland depth and carbon content data is independently confirmed by laboratory analysis of core samples. Through GIS-based spatial analysis of the peat areal extent, depth, and carbon content data, we conservatively estimate the total area of WSL peatlands at 592,440 km^2, the total peat mass at 147.82 Pg, and the total carbon pool at 70.21 Pg C. Our analysis concludes that WSL peatlands are more extensive and represent a substantially larger carbon pool than previously thought: Previous studies report 9,440–273,440 km^2 less peatland area and 15.11–30.19 Pg less carbon than found in this analysis. The complete digital database is freely available for scientific use at http://arcss.colorado.edu/data/arcss131.html. *INDEX TERMS:* 1030 Geochemistry: Geochemical cycles (0330); 1890 Hydrology: Wetlands; 4806 Oceanography: Biological and Chemical: Carbon cycling; *KEYWORDS:* RESURS, remote sensing, Vasyugan Bog, geographic information systems, peatland carbon pool, West Siberian Lowland

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1. Introduction

[2] Northern peatlands play a dual role in the global cycles of carbon dioxide (CO_2) and methane (CH_4), both removing CO_2 from the atmosphere (through plant production and peat accumulation) and emitting CO_2 and CH_4 to the atmosphere in large quantities. Natural peatlands are currently a sink for CO_2 and a source of methane [*Roulet*, 2000]. *Gorham* [1991] estimates the carbon pool of boreal and subarctic peatlands at 455 Pg C, about one fifth of the global terrestrial total (2190 Pg C [*Houghton et al.*, 1996]), or two thirds of the atmosphere's carbon content (750 Pg C). Numerous authors have speculated that northern stocks of peat carbon may become vulnerable to peat decomposition under a warmer, drier climate [*Gorham*, 1991; *Oechel and Vourlitis*, 1994; *Woodwell et al.*, 1998]. Northern peatlands may therefore play an important feedback role in future climate change owing to mobilization of sequestered carbon stocks and their return to the atmosphere or release to surface water [*Freeman et al.*, 2001].

[3] The major northern peatlands are distributed in Canada and the Russian Federation. In Canada, organic soils associated with peatlands have been estimated at

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1.13 million km^2, approximately 12% of the land area of Canada [*Zoltai and Pollett*, 1983]. *Tarnocai* [1998] estimates that Canada contains about 1.24 million km^2 of peatland/organic soils, storing about 154 Pg C. In Russia, peatlands have been studied for a number of different purposes and from different perspectives [*Botch et al.*, 1995], leading to widely varying estimates of peatland area and carbon content. Area estimates range from 0.71 million km^2 [*Tiuremnov*, 1976] to 1.50 million km^2 [*Kivinen and Pakarinen*, 1981], 1.16 million km^2 [*Stolbovoi*, 2002] and 1.65 million km^2 [*Botch et al.*, 1995]. Using multiple data sources, *Botch et al.* [1995] also estimate a carbon pool of 214 Pg C for peatlands of the Russian Federation. In addition, *Stolbovoi* [2002] recently published a smaller figure of the Russian peat carbon pool at 156 Pg C in the 0–2.0 m layer based on the 1:2.5 million soil map.

[4] West Siberian Lowland (WSL) peatlands are a larger carbon pool than previously thought and represent a long-term carbon dioxide sink and global methane source since the early Holocene [*Smith et al.*, 2004]. However, detailed, spatially explicit inventories of WSL peatland area and carbon content have never been published. Field studies of WSL peatlands have been carried out since the 1950s, driven primarily by petroleum exploration. Geoltorfrazvedka, a special body of the Russian Federation Geological Survey, conducted extensive fieldwork in areas mainly south of the permafrost limit, with results presented in unpublished written reports. In the late 1960s, Geoltorfrazvedka produced a series of 1:1,000,000 scale peatland maps of West Siberia, using these field data in conjunction with aerial photographs [*Markov*, 1971]. These maps were associated with a set of printed data reports, arranged by administrative regions and containing measurements of peat area (*A*), peat mass (*M*), mean peat depth (D_m) and mean ash content (S_m) for most peat patches on the maps.

[5] Using the Geoltorfrazvedka reports, Russian scientists have made several estimates about the area and peat mass of WSL peatlands over the past three decades (Table 1), starting with *Neustadt* [1971]. These estimates in Table 1 vary considerably depending upon the methods used and the geographic areas included. It is generally agreed that the total carbon pool of WSL peatlands was underestimated largely due to lack of data in remote regions, which were not included in the Geoltorfrazvedka inventories. In particular, previous estimates were limited to the forest and forest-steppe belt, and excluded tundra peatlands in the northern regions of the WSL. Furthermore, geographic information systems (GIS) were not used in these analyses, preventing full utilization of peatland maps and associated field data. Finally, these earlier estimates did not use updated inventories that were first available in unpublished form beginning in 2000.

[6] Here, we derive new estimates of peatland area and total carbon pool for WSL peatlands using a GIS compilation and inventory of multiple data sources. From the resulting GIS database, we estimate the complete carbon pool of WSL peatlands and analyze its spatial distribution. The inventory is validated using high-resolution satellite imagery and our own field core measurements, allowing computation of a confidence level for the derived carbon pool estimate. As such, this study represents the first high-resolution, spatially explicit peat carbon pool estimate for West Siberia.

Table 1. Previously Published Estimates of Area, Peat Mass, and Carbon Pool of WSL Peatlands

Author	Year	Area, km^2	Peat Mass, Pg	Carbon Pool, Pg C
Neustadt	1971	325,380	93.08	44.21[a]
Tiuremnov	1976	341,000	109.7	52.10[a]
Sabo et al.	1981	319,000		
Davydova and Rachkovskaya	1990	400,000	90	42.75[a]
Vompersky et al.	1994		84.26	40.02[a]
Efremova et al.	1997			42.4
Vompersky et al.[b]	1999	583,000		
Efremov and Efremova	2001	464,000	108.67	51.61[a]
Yefremov and Yefremova	2001			55.1
This study	2004	592,440	147.82	70.21

[a]Carbon pool estimate is not made in this publication; it is calculated here from peat mass using R = 52% (carbon percentage of organic material) and L_m = 91.3% (mean loss-on-ignition).
[b]*Vompersky et al.* [1999] used a Russian soil map in their area estimation.

2. Establishment of a GIS Database for WSL Peatlands

[7] This section describes the data sources and procedures used for construction of the GIS database. The final GIS database contains nearly 10,000 peat patches (i.e., isolated peatlands), their associated peat properties, field core data, and satellite images.

2.1. Data Sources and Map Collection

[8] The GIS database was constructed from compilation, translation, and digitization of all accessible published and unpublished field data and ancillary maps on WSL peatlands and wetlands. In addition to the original 1971 Geoltorfrazvedka reports and maps [*Markov*, 1971], updated peatland maps, and reports were collected from the Novosibirsk Institute of Geology, Geophysics and Mineral Resources, the Russian Ministry of Natural Resources, which are based on revised Geoltorfrazvedka data so as to include new field data to 1999 [*Matukhin and Danilov*, 2000]. These revised data contain new peat patches and numerous patches that are updated with a higher level of detail. Updated regions include Krasnoyarsk [*Matukhin*, 1997] and elsewhere in the WSL, with the exception of western Sverdlovsk. Therefore our inventory uses the older 1971 Geoltorfrazvedka data set in the Sverdlovsk region. The Geoltorfrazvedka and Novosibirsk maps have scales of 1:1,000,000, and represent peatlands as “oligotro-phic” (bog), “transitional,” “eutrophic” (fen), “mixed,” or “undetermined” classes. The undetermined class represents those peatlands not studied in the field. The numeric label for each peat patch on the Novosibirsk maps points to associated field data in a series of printed reports arranged by administrative region. Spatial coverage of the Novosibirsk data sets is restricted mainly to the area south of the continuous permafrost limit, with very limited coverage in northern tundra areas. Therefore peatlands in northern regions were inventoried using a 1:2,500,000 scale

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map of West Siberia wetlands published by State Hydrological Institute (SHI) in Leningrad [*Romanova et al.*, 1977]. Unlike the Novosibirsk maps, no ancillary data reports are associated with individual wetlands. Relatively good agreement in spatial coverage between the Novosibirsk and SHI data sources was found in areas south of the continuous permafrost limit. Comparison of the SHI wetland map with the Soil Map of Russian Federation [*Fridland*, 1988] also finds comparable wetland extent in the forest-tundra and tundra regions, though some differences exist in the spatial distribution of individual wetlands and peat soils.

2.2. GIS Peat Layer Generation

[9] The Novosibirsk maps represent large and small peatlands differently. Large peatlands are shown with their actual borders delineated and may be comprised of different peatland classes, while small ones are shown as dots with their areas recorded only in the associated data reports. Small peatlands were therefore digitized as point data structures, and large peatlands as polygon data structures within the GIS. A composite peatland containing two or more peat classes is regarded as a single peat patch even though it is represented by more than one polygon. Maps were scanned using a large-format digital map scanner, with vector extraction carried out using the ESRI® ArcGIS™ system. This procedure yielded 7127 peat patches from the Novosibirsk and the Geoltorfrazvedka maps. Property data such as A, M, D_m, and S_m associated with each patch were stored in an attribute table within the GIS. The table represents information gathered from the field over the past 40 years by various organizations with differing levels of precision. Some peat patches were well inspected, with numerous measurements of peat properties taken, while others were investigated less thoroughly. Those peatlands marked as undetermined have no field data associated with them. All peat properties in the field data reports were manually digitized. These attributes were then assigned to their associated peat patches according to their unique label identifiers in the data reports and maps. The derived high-resolution polygon maps cover the southern and central areas of the WSL (roughly south of ~66°N).

[10] Peatlands in the northern portion of the WSL were digitized from the SHI wetland map as 2564 patches and categorized as undetermined with respect to attribute data. The SHI and Novosibirsk sources were then merged to produce the WSL GIS peat layer (Figure 1), containing 9691 peat patches. About 30,000 peat property measurements were digitized and incorporated as attribute data associated with these patches. This layer covers the entire WSL to a high level of detail (see insert, Figure 1). In addition, 2796 water bodies larger than 1 km^2 contained within peatlands were also delineated and digitized as a GIS peatland lake layer (Figure 1).

[11] All layers are maintained in a Lambert Conformal Conic map projection with a central meridian at 75°E, and two standard parallels at 70°N and 50°N, preserving the original projection of the source data. Map-based area calculations in this paper were carried out with a Lambert Azimuthal Equal Area map projection to reduce area distortion.

2.3. Satellite Images

[12] The Russian RESURS-01 satellite payloads a multispectral optical-mechanical radiometer (MSU-SK), acquiring images using a conical scanning mechanism with a spatial resolution of ~150 m in five spectral bands (0.5–0.6 μm, 0.6–0.7 μm, 0.7–0.8 μm, 0.8–1.0 μm, and 10.4–12.6 μm). Two MSU-SK visible/near-infrared images were acquired over the main peatland areas in the WSL (Areas 1 and 2, Figure 1) on 3 June 1997 and 17 July 1998, covering approximately 400 km × 615 km and 615 km × 430 km, respectively. These data were used to independently validate the peat patch areas of the GIS peat layer.

2.4. Field Measurements

[13] Depth measurements for some WSL peatlands have previously been published in Russian and international studies of peatland and vegetation history [*Forman et al.*, 2002; *Kremenetski et al.*, 2003]. We compiled field depth measurements at 62 locations from this literature to generate a GIS layer of "pre-existing Russian cores" (PERC, black triangles in Figure 1). Eighty-seven peat cores (open circles in Figure 1) were also collected by the authors during summer field campaigns in 1999, 2000, and 2001 [*Smith et al.*, 2000, 2004], producing a layer of "UCLA (University of California, Los Angeles) cores" in the GIS database. These coring sites were planned in the sampling design to be spatially dispersed as widely as possible. Field samples were normally collected in peatlands within kilometers of roads and other access routes. The field data from these cores provide new observations of peat depth, bulk density, and loss on ignition (LOI at 550°C for 1–2 hour). Collectively, these field depth data provide 149 independent measurements, which we here use to independently validate the Novosibirsk data sets (section 3.2) and to interpolate missing depth values, particularly in the northern regions (section 4).

3. Validation of Geoltorfrazvedka and Novosibirsk Data Sets

[14] The Geoltorfrazvedka and Novosibirsk maps and data reports are the primary data sources used in this study, but do not contain error estimates, specifications for the laboratory analyses, or other descriptors of data quality. Therefore a validation process was developed to assess their data quality. Each of the four patch properties used to compute carbon content (area, depth, bulk density, and LOI) were independently assessed. Mapping accuracy of peat patch areas was tested using high-resolution RESURS-01 satellite images. Patch depths were validated using both PERC data and our own field measurements. Bulk density and LOI were checked using our own core data. These procedures are described in detail in the following sections.

3.1. Peat Area

[15] Peat patch areas from the GIS peat layer are validated using the two RESURS-01 images (Figure 1) in peat-extensive regions in central WSL. In these areas,

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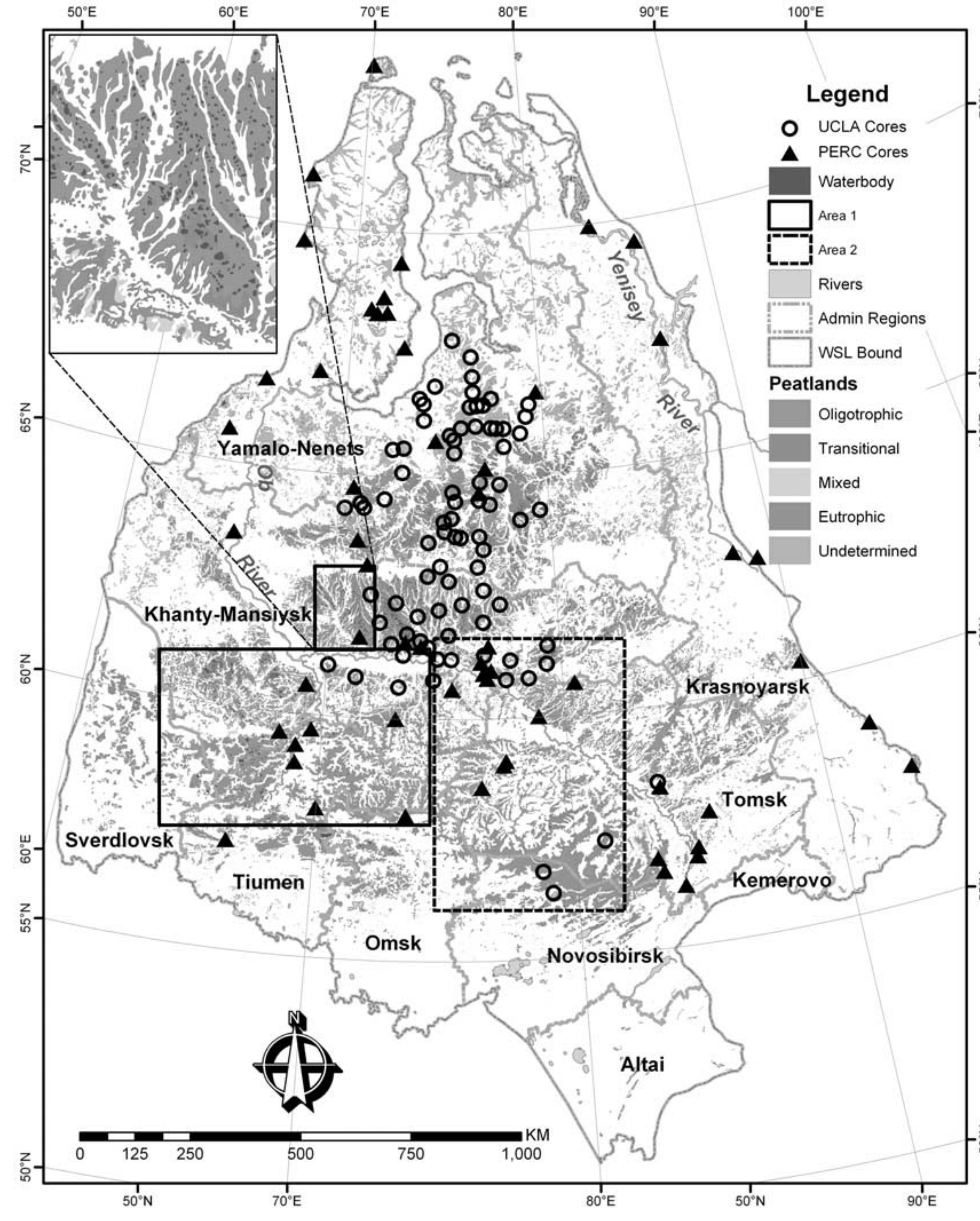

Figure 1. GIS database of WSL peatlands, featuring a detailed peat layer and a peatland lake layer. The peat layer was compiled from the 2000 Novosibirsk peat maps, the 1971 Geoltorfrazvedka peat maps, and the 1977 wetland map. The layer contains 9,691 peat patches, composed of 12,401 polygons showing peat type (oligotrophic, transitional, eutrophic, mixed, or undetermined). Each patch has attribute data: peat area (A), mean depth (D_m), mean bulk density (ρ_m), and mean LOI (L_m, loss on ignition). The peatland lake layer contains 2,796 large water bodies within peatlands. The 'Area 1' and 'Area 2' boxes outline the coverage of two RESURS-01 images used for validating the GIS peat layer. Field validation of peat depth and physical properties are provided by UCLA cores (open circles) and PERC cores (black triangles). See color version of this figure at back of this issue.

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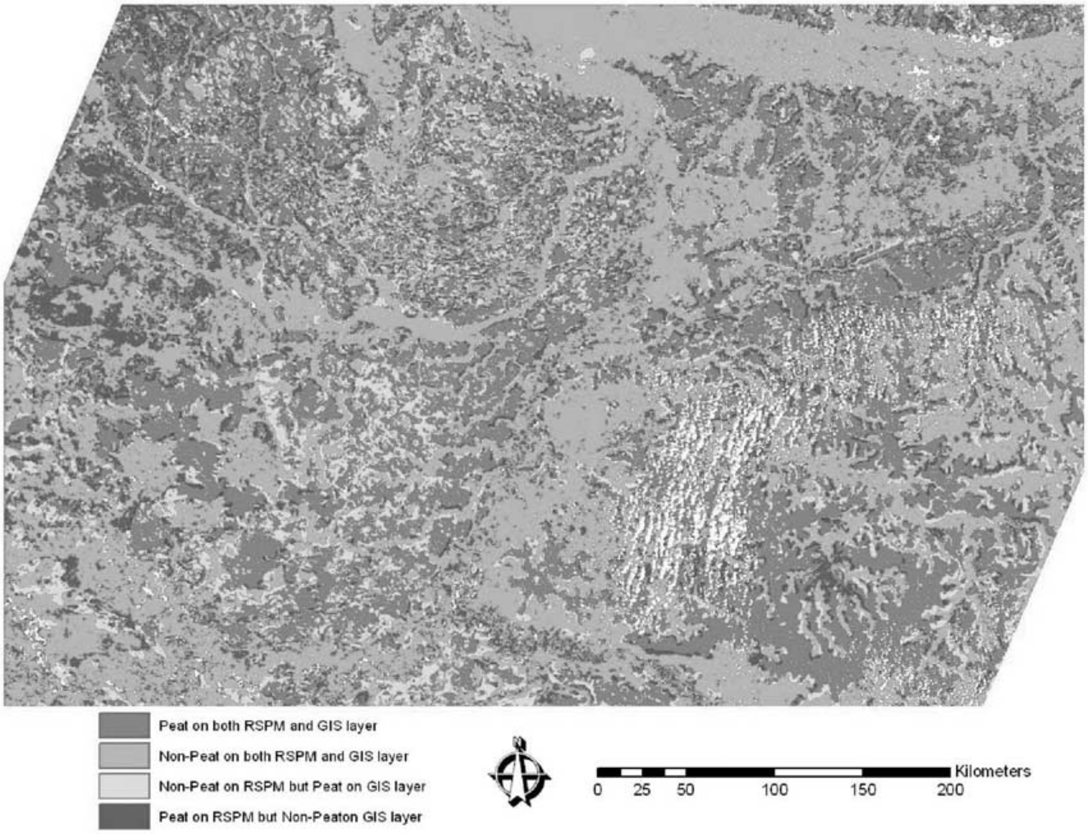

Figure 2. Peatland area validation for Area 1. Overlay of the remotely sensed peat maps (RSPM) with the corresponding portion of the GIS peat layer yields four categories: peat on both maps (red), non-peat on both maps (green), non-peat on RSPM but peat on the GIS peat layer (yellow), and peat on RSPM but non-peat on the GIS peat layer (blue). The red and green colors correspond to agreement, while yellow and blue show disagreement between RSPM and the GIS layer. See color version of this figure at back of this issue.

the contrast between vegetation covers on peatlands (mostly *Sphagnum*) and the surrounding areas (mainly conifers and birch) is so distinct that peatlands can be well identified in summer season satellite imagery, in which misclassification does not impose a serious problem. At high latitudes, northward of the tree line, the absence of trees makes peatland delineation from satellite images difficult. These images were processed using the ENVI® image-processing software to generate remotely sensed peat maps (RSPM). The procedures include geo-registration of the images to the GIS peat layer, image classification using the maximum likelihood classifier, and regrouping of the derived classes into categories of peat, non-peat, and clouds (if any). Since classified images appear grainy with isolated pixels, RSPM maps are generated after removing these isolated pixels from the regrouped image.

[16] Visual inspection shows general agreement between the RSPM map and the GIS peat layer, although the latter tends to generalize peatland extent and boundaries, and ignore very small peatlands. Quantitative comparison is enabled by overlaying the RSPM map with the GIS peat layer, yielding a comparative image with four categories: (1) peat on both maps (red), (2) non-peat on both maps (green), (3) non-peat on RSPM but peat on the GIS peat layer (yellow), and (4) peat on RSPM but non-peat on the GIS peat layer (blue). Figure 2 shows the four-categorized comparative image of Area 1, and Table 2 lists the pixel counts for each category (cloud-covered areas are not included in this validation). Good agreement (73.4%, i.e., the total percentage of red and green areas) is found between the RSPM and the GIS peat layer, and peatland percentages are very similar between the two sources (41.9% and 42.2% for GIS and RSPM, respectively). Similar results are found for Area 2 (73.5% agreement with 37.8% and 37.9% peatland percentage for GIS and RSPM, respectively). In both test areas, the total peat areas estimated from the remotely sensed peat map and the GIS peat map differ less than 0.3%, though site-specific agreement is as low as 73.4%. The fortuitous cancellation is not random, but instead largely reflects slight offsets with geo-registration between the two data sets. These offsets were a result of registering the satellite image (150-m resolution) to the coarser scale GIS peat layer (1:1 million scale). Precise co-registration would require a detailed large-scale base map, which does not currently exist for West Siberia. However, despite these small locational offsets, the shape and size of

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Table 2. Peat Area Validation Using RESURS-01 MSU-SK Images[a]

		Peat (RSPM)	Non-Peat (RSPM)	Subtotal[b]
Area 1	peat (GIS)	2,917,187[b]	1,330,097[c]	4,247,284 (41.9%)[d]
	non-peat (GIS)	1,361,546[e]	4,529,698[f]	5,891,244 (58.1%)
	subtotal	4,278,733[g] (42.2%)	5,859,795 (57.8%)	10,138,528 (100%)
Area 2	peat (GIS)	2,835,218	1,498,162	4,333,380 (37.8%)
	non-peat (GIS)	1,508,472	5,633,860	7,142,332 (62.2%)
	subtotal	4,343,690 (37.9%)	7,132,022 (62.1%)	11,475,712 (100%)

[a]GIS peat layer is validated by the satellite images in both Area 1 and Area 2 (Figure 1). The peat areas estimated from the GIS peat layer and from the RESURS-01 satellite images differ by less than 0.3%.
[b]Pixel number of red areas in Figure 2 (i.e., peat on both RSPM and GIS layer).
[c]Pixel number of yellow areas in Figure 2 (i.e., non-peat on RSPM but peat on GIS layer).
[d]Subtotal of peatlands measured from GIS peat layer, with pixel percentage in parentheses.
[e]Pixel number of red areas in Figure 2 (i.e., peat on RSPM but non-peat on GIS layer).
[f]Pixel number of green areas in Figure 2 (i.e., non-peat on both RSPM and GIS layer).
[g]Subtotal of peatlands measured from RSPM.

the peatlands at local scales are in remarkable agreement between the two data sets. If they could be better co-registered to a high-resolution base map, a significant shrinkage of the disagreement areas (i.e., yellow and blue areas) would result. A secondary effect is that satellite-based classifications tend to identify many small peatlands, which are ignored in the more generalized peat maps. However, the satellite classifications also delineate small gaps within contiguous peatlands owing to variations in peatland vegetation cover that are not recorded on the more generalized peat maps. The net result of both effects is a fortuitous cancellation of their differences (Table 2).

3.2. Peat Depth

[17] Reliability of the Novosibirsk peat patch depth estimates was tested using independent field measurements of peat depth. Correspondence between these field cores and their surrounding peat patches was established using GIS utilities. Only those cores (i.e., 49 PERC cores and 68 UCLA cores) located within well-studied peat patches (i.e., with peat property data available in Russian data reports through fieldwork) were used in the validation. If a peat patch contains two or more cores, the average of their values was used as the field measurement. Figure 3a reveals a modest positive correlation between these point data and corresponding patch-averaged values for the surrounding peat patch from the GIS peat layer. The *t*-test ($\alpha = 0.05$) shows that the mean of the Novosibirsk depth data is not significantly different from those of UCLA and PERC depth measurements, though the Novosibirsk depths on average are 3% and 5% less than the depths from the UCLA and PERC cores, respectively (Table 3). A likely explanation for this is that the PERC cores were collected from various sources, some of which were specifically cored in deep peat for the purpose of Quaternary paleoenvironmental research. In contrast, the Geoltorfrazvedka and Novosibirsk data report spatially averaged peat depth; and the UCLA cores report random point depths. Ground-penetrating radar (GPR) transects taken at several UCLA core locations [*Dubinin et al.*, 2000] suggests that a random point peat depth is quite representative of surrounding depth conditions. To quantify this similarity, depth readings were taken every 20 cm along two orthogonal GPR profiles of the core site at (61.546°N, 72.715°E) (Figure 4). Close agreement is found between the point measurement (1.25 m) and profile data ($\mu = 1.29$ m, $\sigma = 6.44$ cm). This result, combined with the reasonable agreement between our field data and the data reports, suggests a general validation of the latter, at least in the general vicinity of the peat core.

3.3. Peat Physical Properties

[18] Carbon content is directly proportional to bulk density and LOI. Mean bulk density (ρ_m) of a peat patch may be recovered from Novosibirsk values of peat mass, area, and mean depth as $M/(A \times D_m)$, and mean LOI (L_m) may be derived as $1 - S_m$. The correlation between Russian patch-averaged bulk density data and our own laboratory data from cores shows considerable scatter (Figure 3b, Table 3). Our field data show in Figure 5 a significant increasing trend of bulk density from south (as low as 0.056 g/cm^3) to north (as high as 0.418 g/cm^3). The higher bulk density in the north is due to the higher ash content and the lower water content found in permafrost peatlands. The Russian patch-based data average significantly less (~26%), indicating use of the Geoltorfrazvedka and Novosibirsk data sets to be conservative with regards to carbon pool estimation. The Russian data mainly cover the southern and central WSL, whereas our field data contain several high-density cores in the northern areas. This may be an explanation of the apparently low mean of Novosibirsk data. We also note that the Russian bulk density data ($\mu = 0.094$ g/cm^3, Table 3) are comparable to values reported from a high-resolution study in Salym-Yugan Mire in southern WSL ($\mu = 0.093$ g/cm^3 [*Turunen et al.*, 2001]). Similarly, Russian patch-averaged estimates of LOI average ~5% less than our laboratory measurements (Figure 3c, Table 3), suggesting utilization of the Russian data sets to be conservative for the purpose of carbon pool estimation.

[19] Carbon density (CD), defined as the amount of carbon per unit area, may be derived from peat depth, bulk density, LOI, and carbon percentage of the organic material (R) as $CD = D \times \rho \times L \times R$. We assume a conservative value of 52% for R in this paper (see section 5). Correlation between Russian patch-based carbon density and UCLA core data shows considerable scatter. This is not surprising given the spatial heterogeneity of peat growth rates and compaction even at a local scale, but data ranges are quite similar between the two sources (Figure 3d, Table 3). Russian patch-based calculations of carbon density average

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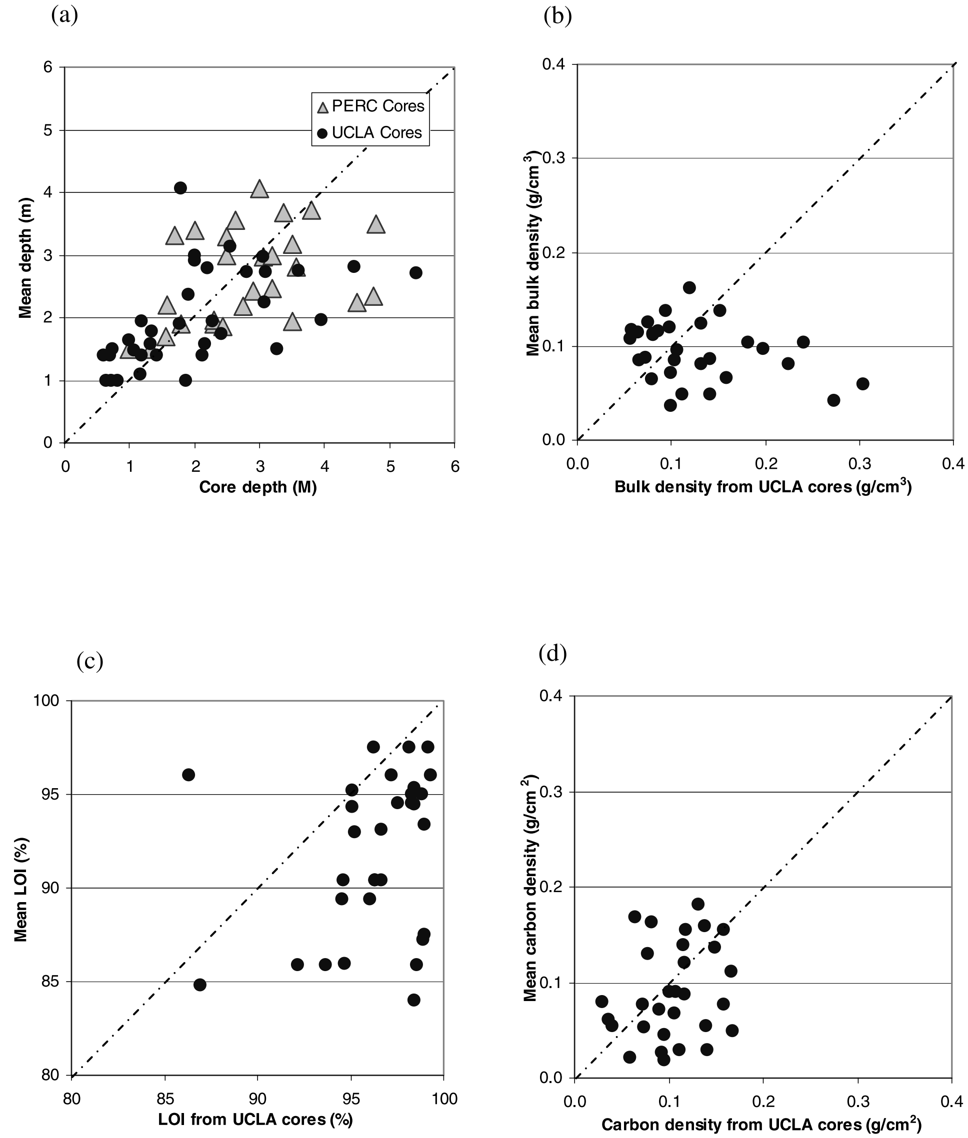

Figure 3. Comparison of Novosibirsk peat depth and property data with UCLA and PERC cores. (a) peat depth, (b) peat bulk density, (c) LOI, and (d) carbon density.

~14% less than our core-based estimates, but the difference between the means of the two data sets is not statistically significant from the *t*-test.

4. Interpolating the Incomplete Data Records by Geostatistics

[20] Approximately 40% of the digitized patches do not contain data values for patch depth, bulk density, and/or LOI. These missing data were interpolated from surrounding peat patches using the Ordinary Kriging method in the ArcGIS™ Geostatistical Analyst extension [*Johnston et al.*, 2001]. Ordinary Kriging assumes that proximal peatlands are more similar than those farther away, and is a statistically optimal interpolation based on spatial autocorrelation characterized by semivariograms. This method involves four procedures: exploring the empirical semivariogram plot, fitting a model to the empirical semivariogram plot, developing the optimal model through model comparison and performance diagnostics, and making predictions using the optimal model for locations with unknown values from nearby locations with known values. All available depth data (including core depth measurements and those from the Geoltorfrazvedka and Novosibirsk reports) were composed to form a layer of depth measurements. For the model validation purpose, the depth layer was randomly split into two data sets, one containing 90% of data points, and the other with the remaining 10%. Though the 90% separation is an arbitrary value, we found it was a good choice for developing a reliable model. The larger data set was then used to develop an interpolation model. The splitting of the data sets was replicated several times to obtain a relatively consistent interpolation model as the optimal model. The

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Table 3. Averaged Peatland Depth and/or Physical Properties, as Compared Between Pre-Existing Russian Cores (PERC), Our Own Cores (UCLA), and the Corresponding Peat Patches From the GIS Database[a]

Properties	Source	Core Measurements		Novosibirsk Data Reports		Significance of $\mu_1 \neq \mu_2$ (*t*-test)
		μ_1	σ_1	μ_2	σ_2	
Depth, m	PERC	2.797	1.004	2.651	0.757	no
Depth, m	UCLA	2.050	1.160	1.992	0.765	no
Bulk density, g/cm^3	UCLA	0.128	0.065	0.094	0.031	yes
LOI, %	UCLA	96.268	3.164	91.803	4.226	yes
Carbon density, g/cm^2	UCLA	10.511	3.817	9.006	4.963	no

[a]Here μ and σ are mean and standard deviation of samples, respectively. The means of the data sets are compared using *t*-test (α = 0.05) analyses.

interpolation model was then used to predict depth for the smaller data set. Good correlation (R^2 = 0.6343, n = 623) was found between the predicted and observed values for the smaller data set, confirming satisfactory validation of the interpolation model (Figure 6). The model was then used to predict mean depths for peat patches lacking depth values in the GIS database. Missing values of bulk density and LOI were similarly interpolated.

5. GIS-Based Carbon Pool Estimation

[21] A peat carbon pool may be estimated at various levels of detail. The simplest estimation method employs a homogeneity model, which assumes that peatlands have uniform physical characteristics and may therefore be characterized by single averaged values of depth (D_m), bulk density (ρ_m), LOI (L_m), and carbon percentage (R). The peat carbon pool (CP) is then computed as

$$\mathrm{CP} = A \times D_m \times \rho_m \times L_m \times R. \qquad (1)$$

[22] Assumption of peat homogeneity is required when data on peat properties are sparse and the study area is large [e.g., *Gorham*, 1991]. However, the homogeneity model ignores spatial variations in peatland properties and is sensitive to errors in assumed mean values of the input parameters. For example, an erroneous increase in assumed depth from 1 m to 1.5 m yields a 50% overestimate of the carbon pool.

[23] *Botch et al.* [1995] suggested that the estimation of carbon pools should include regional differences in peat

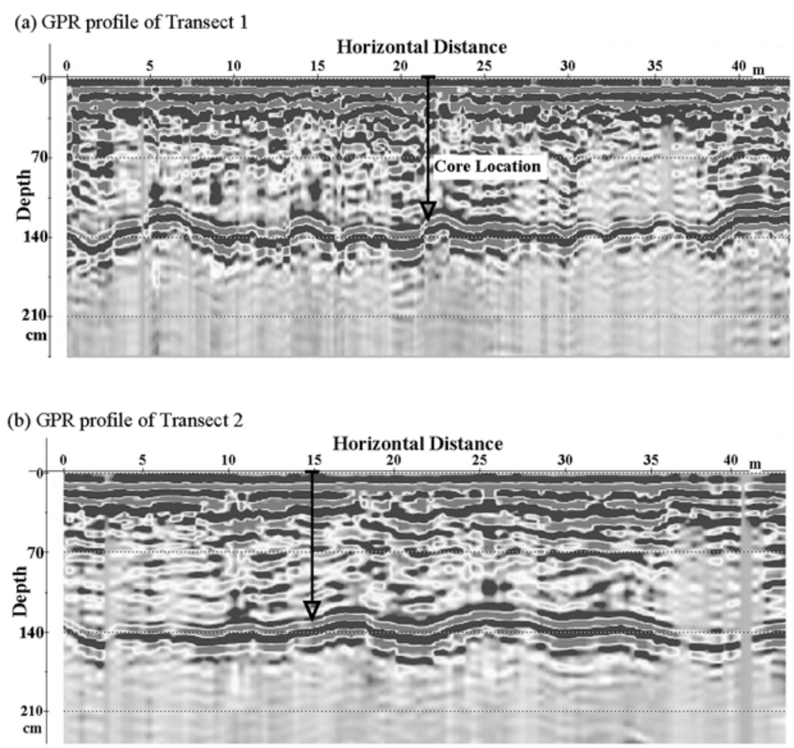

Figure 4. Ground-penetrating radar profiles. Two intersecting 43 m GPR profiles were collected at a UCLA core site (61.546°N, 72.715°E). Profile-averaged depth (1.29 m, σ = 0.06 m) corresponds well with the single measurement of core depth (1.25 m). See color version of this figure at back of this issue.

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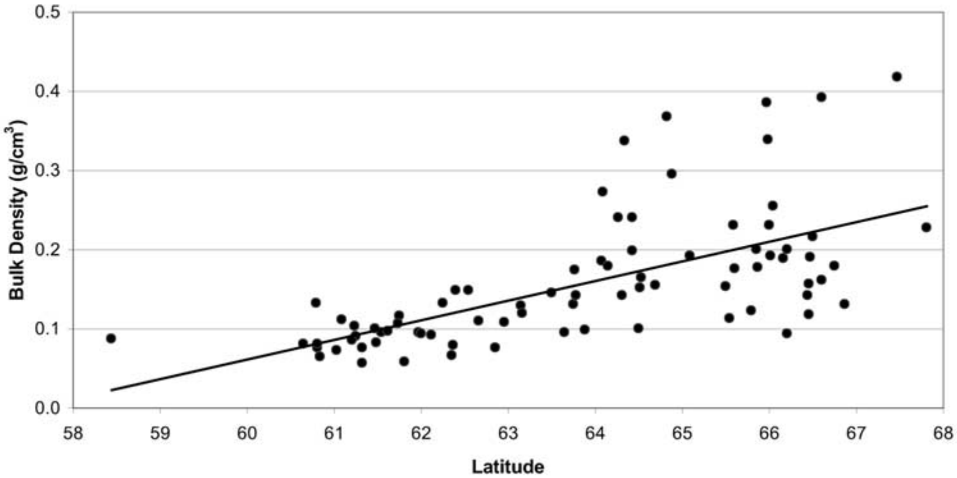

Figure 5. UCLA bulk density measurements show a significant increasing trend from south to north. A simple linear regression model show that $Y = 0.0248X - 1.4276$ with $R^2 = 0.4024$, where Y is bulk density (g/cm^3) and X is latitude (degrees).

properties. They divided the former Soviet Union into 10 peatland zones, with each treated as having homogeneous physical properties. Under this regionalization scheme, the WSL contains five zones. The region-based model is an improved version of the homogeneity model, but the heterogeneities resolved are coarse and the assignment of mean peat properties is largely based on expert judgment.

[24] This paper uses a high-resolution, patch-explicit model to estimate CP. Furthermore, the model is based on observational data. This patch-based model is easily implemented in a GIS as

$$\mathrm{CP} = \sum_{i=1}^{n} A_i \times D_i \times \rho_i \times L_i \times R_i, \tag{2}$$

where, n is the total number of peatland patches (n = 9,691 for the WSL); A_i, D_i, ρ_i, L_i, and R_i are the area, mean peat depth, mean bulk density, mean LOI, and the carbon percentage of the organic material for patch i, respectively.

[25] The carbon percentage of peat organic material (R) has been estimated differently by various researchers. *Efremov and Efremova* [2001] show that mean R varies little among different peat types in West Siberia, averaging 50.4%, 51.8%, and 53.9% for eutrophic, transitional, and oligotrophic peat, respectively. Similarly, *Lapshina and Pologova* [2001] provide 51.8 ± 2.5% for main WSL peat types. In western Canada, *Vitt et al.* [2000] determine a value of 51.8 ± 4.7%. Here we assume a constant value of R = 52%, for three reasons: (1) Carbon percentage R is known to vary only slightly little among different types of WSL peatlands [*Efremov and Efremova*, 2001]; (2) the GIS peat layer describes four major peatland types based on surface characteristics only, with no indication of subsurface peat type; and (3) assumption of R = 52% is conservative, as compared to values previously assumed in other studies, for example, 58% by *Tiuremnov* [1976], and 57% (before LOI, i.e., ash included) by *Botch et al.* [1995].

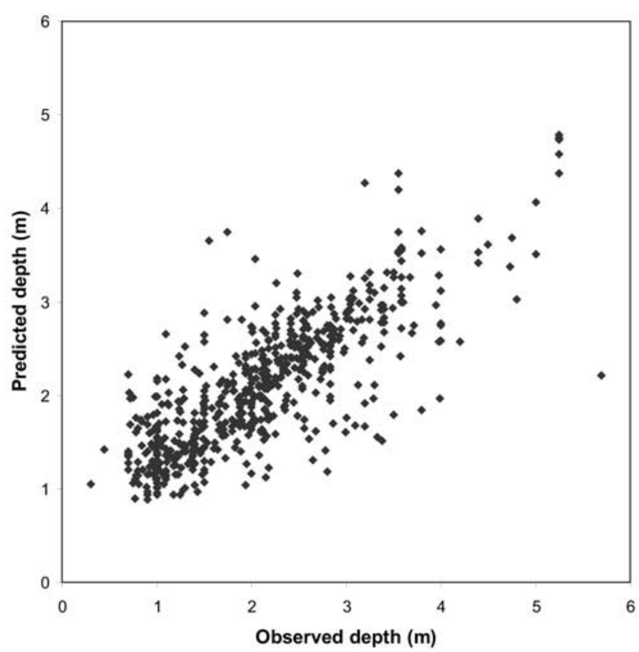

Figure 6. Validation of the Ordinary Kriging peat depth interpolation model using split data sets. The depth data set was randomly split into one part containing 90% of the data points, and the other with the remaining 10%. The larger data set was used to develop the interpolation model to predict peat depths for the smaller data set, and measurements in the smaller data set were used to validate the model by comparing the predicted depths with the original depth measurements at these locations. Good correlation (R^2 = 0.6343, n = 623) between the predicted and the observed values suggests that the interpolation model is reasonable.

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[26] Application of equation (2) for all 9691 peat patches yields a carbon pool of 72.55 Pg C. This figure was then corrected to account for the mineral tundra effect and the presence of large water bodies that are commonly found within peatland boundaries. In permafrost areas of the WSL, peat cover typically exhibits a complex pattern of polygonal peat patches, particularly in mineral tundra. In such areas, peatlands are commonly interspersed at a small spatial scale with areas of exposed substrate containing little or no peat, leading to overestimation of peat carbon storage from generalized maps. These tundra regions have been poorly investigated, with little data available because of their remoteness and the challenging environment. Owing to the lack of information, we arbitrarily assumed peat coverage to be 50% in such peatlands, resulting in a correction of −2.83 Pg C to the carbon pool estimate. A similar correction was made for 2796 large peatland lakes (occupying 11,034 km^2) contained in the GIS peatland inventory. In the WSL these peatland lakes are typically shallow and commonly underlain by peat. Therefore underestimation of the carbon pool can result if peat storage beneath these lakes is ignored. Conversely, if these lakes themselves are ignored and their areas are assumed to be comprised fully of peat, the carbon pool will be overestimated. Because water depth data are not available for these lakes, we arbitrarily assumed them to be underlain by a peat layer of one half the thickness of the surrounding peatland. This correction adds 0.49 Pg C to the total carbon pool estimate.

[27] After the above adjustments, our inventory yields a total carbon pool of 70.21 Pg C. Total area, total peat mass, and organic mass are estimated at 592,440 km^2, 147.82 Pg, and 135.02 Pg, respectively. These figures are substantially larger than previously published estimates (Table 1). A trend noticeable in Table 1 is that the figures are growing. Many early estimations used the Geoltorfrazvedka data reports, limiting their study areas mainly in the forest and forest-steppe belt of WSL, and produced small but relatively consistent estimates [*Neustadt*, 1971; *Tiuremnov*, 1976; *Sabo et al.*, 1981; *Davydova and Rachkovskaya*, 1990; *Vompersky et al.*, 1994; *Efremova et al.*, 1997]. More recent efforts released larger figures using additional data sources [*Vompersky et al.*, 1999; *Efremov and Efremova*, 2001; *Yefremov and Yefremova*, 2001]. Our estimates are even larger than these recent ones. We attribute this contrast to our spatially explicit, patch-level analysis utilizing all available observational data, and our extension into areas beyond the coverage of the Geoltorfrazvedka and Novosibirsk reports. The total peatland area estimated in this study most closely resembles that of *Vompersky et al.* [1999] constructed with the aid of a Russian soil map.

[28] Figure 7 shows the spatial distribution of the WSL carbon density. About half of the total WSL peatland area and 63.3% of the peat carbon pool (i.e., 44.41 Pg C) are found between 57°N and 61°N, with a mean carbon density of 150.1 kgC/m^2. This area is considered to contain the highest density of peat deposits in the WSL [*Botch and Masing*, 1983]. This area also contains the Great Vasyugan Bog, occupying 63,252 km^2 and containing 10.78 Pg C. Figures 8a and 8b illustrate the latitudinal distributions of peat area and carbon pool, respectively. A bimodal distribution indicates that the carbon pool is divided into a southern pool and a northern pool at roughly 63°N, where the Sibirskie Uvaly Hills bisect the WSL from west to east. The southern pool is centered near 59°N and contains ∼395,000 km^2 of peatlands, comprising ∼76% of the total WSL peat carbon pool. Although the northern pool occupies 33% of the total peatland area, it is less significant in terms of carbon storage (∼24% of the total carbon pool) owing to a general northward reduction of peat depth.

6. Uncertainty Analysis

6.1. Uncertainty in Peatland Area and Physical Peat Properties

[29] Carbon pool (CP) is the product of peat area and carbon density. Errors introduced by the former are likely small as shown from the validation using satellite imagery in section 3.1. The uncertainty is larger, however, in the Novosibirsk estimates of carbon density (note scatter between Novosibirsk and core-based carbon density data, Figure 3d). The magnitude of data scatter between field and Novosibirsk density estimates (Figure 3d) provides one measure of this uncertainty. The mean distances above and below the 1:1 line in Figure 3d represent empirical estimates of potential carbon density overestimation and underestimation, respectively. These estimates represent a general-case scenario in which our core data, taken at a single point within a peat patch, are assumed to reflect perfectly the average peat properties for that patch. These calculations suggest that based on our field measurements, the Novosibirsk patch-scale carbon density may be overestimated by 26% or underestimated by 34%, owing to combined uncertainties in peat depth, bulk density, and LOI. Combining the uncertainties for both peat area and carbon density, the total carbon pool derived from the Novosibirsk data source may be overestimated by as much as 27% or underestimated by as much as 35%.

6.2. Lack of Data From Northern Tundra Peatlands

[30] The density of field data presented in the Novosibirsk reports varies spatially, with maximum densities in the southern WSL and near population centers. Data density decreases to the north, and the reports are wholly absent in tundra areas north of ∼66°N, requiring digitizing of peatland boundaries from a low-resolution SHI wetland map and interpolation of peatland properties from sparse field observations. For this reason, we have conservatively assumed a 100% uncertainty from peatlands not covered by the Novosibirsk data reports in our overall uncertainty analysis for the WSL carbon pool.

[31] To provide a spatially explicit evaluation of carbon pool uncertainty, a "missing-data-index" (MDI) was computed as the area ratio of undetermined (by field visit) (U) to total peatlands (T) within each 1° latitudinal zone,

$$MDI = \frac{U}{T}. \qquad (3)$$

[32] The MDI index ranges from 0 to 1. Values near zero indicate a high confidence level in the carbon pool estimate,

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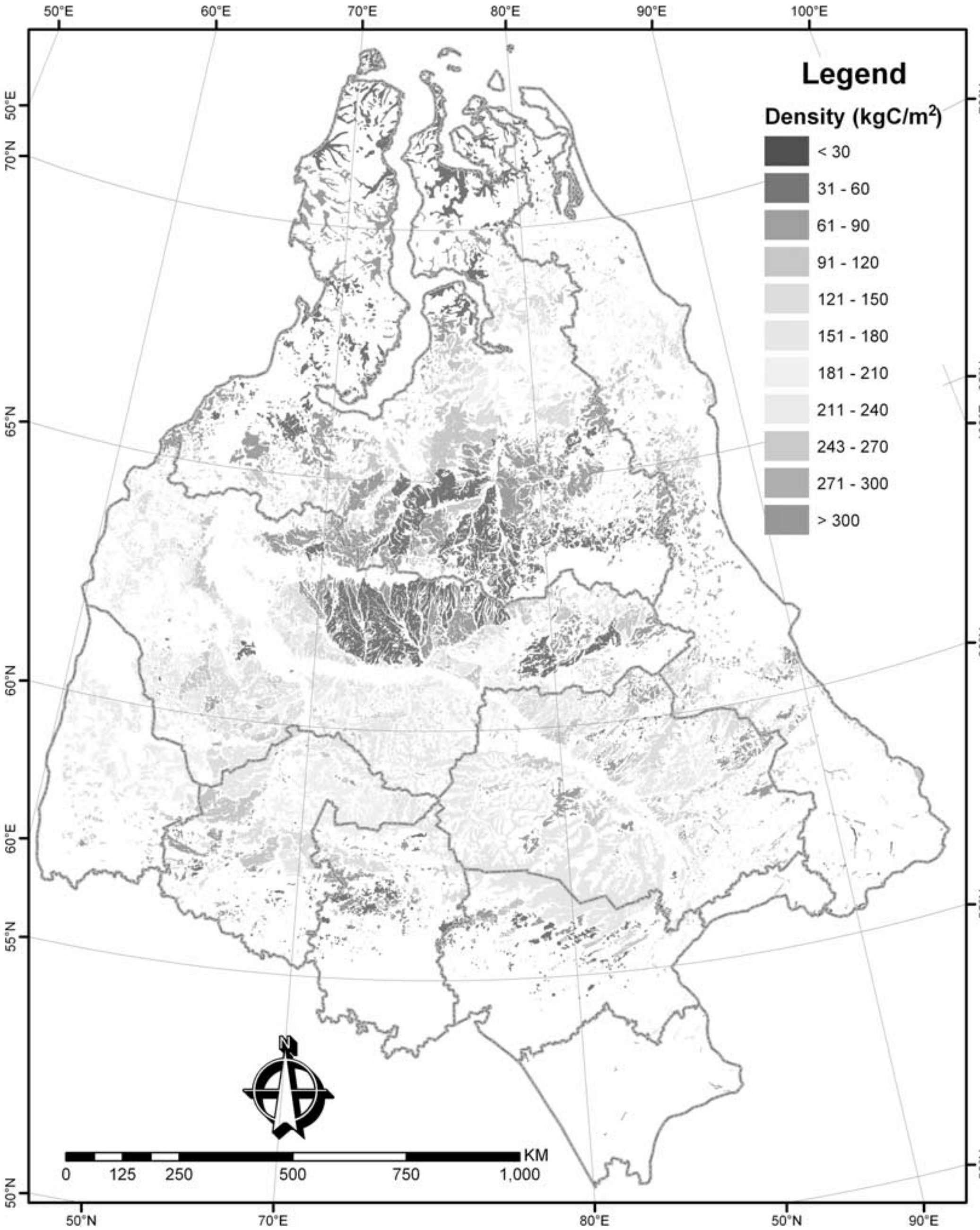

Figure 7. Map of WSL carbon density (carbon per unit area). Higher carbon densities occur in deeper and denser peatlands. Carbon density is greatest near 58°N, but is relatively low near the Sibirskie Uvaly Hills (~63°N). See color version of this figure at back of this issue.

as nearly all the peatlands are well studied. In contrast, high MDI values indicate a high uncertainty in the carbon pool estimate, since that is based largely on peatlands that were not actually measured by field observation. Seventy-six percent of the WSL peatlands are well studied, particularly in the southern and central WSL. Because northern regions are less investigated, the MDI index from 63°N to 66°N increases sharply from 0.16 to 0.9, and approaches 1.0 northward of 67°N (Figure 8b). Combining the missing-data effect and uncertainties in peat area and peat properties, the upper bound of the carbon pool uncertainty is defined as (MDI × 100% + (1 − MDI) × 35%) × CP, and similarly the lower bound is (MDI × 100% + (1 − MDI) × 27%) × CP. The uncertainty of the total WSL peat carbon pool is thus estimated to be −30.03 to 34.48 Pg C. The southern carbon pool (53.55 Pg C) south of 63°N is quite certain

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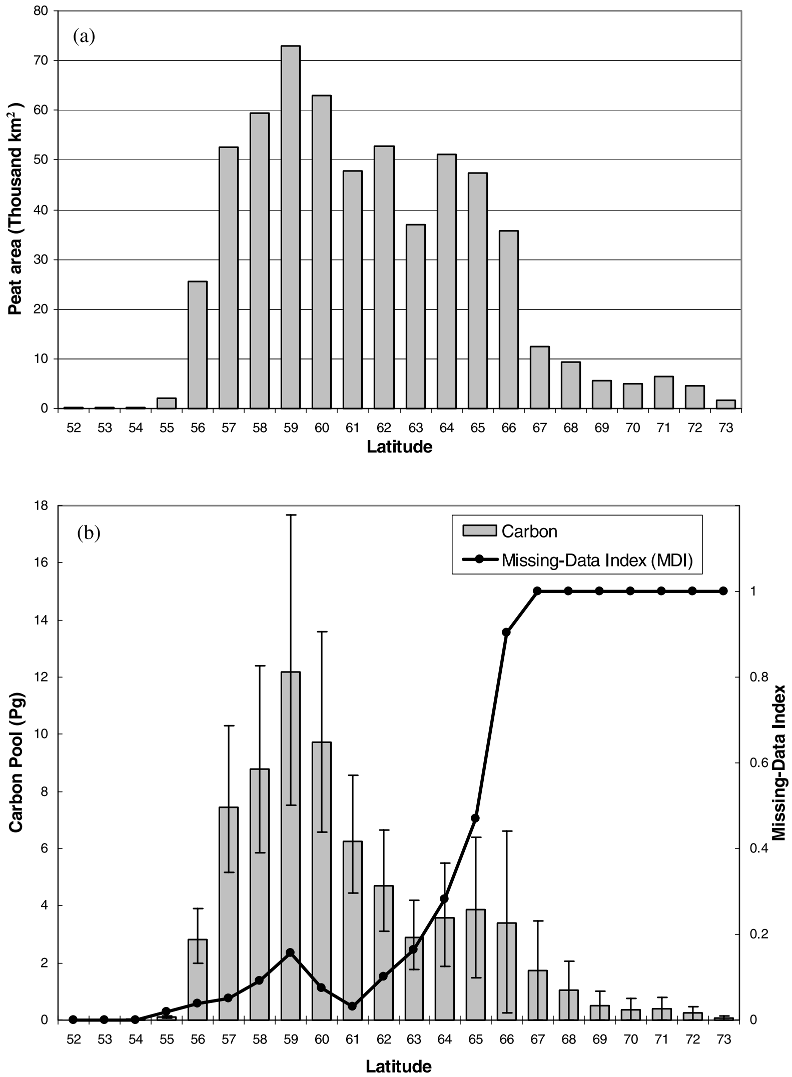

Figure 8. Latitudinal distribution of (a) peatland area, and (b) carbon pool. A bimodal distribution in both histograms indicates that the carbon pool is split E-W at ~63°N by the Sibirskie Uvaly Hills. The southern pool contains about 395,000 km^2 of peatlands and comprises ~76% of the carbon pool. Though the northern peatlands occupy 33% of the total peatland area, they comprise only ~24% of the carbon pool. Error bars on Figure 8b represent carbon pool uncertainties for each 1-degree latitude (Section 6.2). Also shown is the missing-data index (MDI) as a function of the latitude. The MDI increases sharply northward of 63°N owing to a paucity of field data. However, this problem is mitigated by reduced peatland area and thickness, resulting in substantially less carbon storage at high latitudes.

(MDI < 0.2). Note that northern areas of highest MDI index are associated with a small carbon pool (Figure 8b), owing to a general northward reduction of peat depth. We estimate the carbon pool north of 66°N to be 7.78 Pg C, just ~11% of the WSL total. Therefore the poor data quality (MDI > 0.5) north of this latitude introduces a relatively small error to the overall WSL carbon pool estimate.

7. Data Dissemination

[33] The GIS database of WSL peatlands created in this study features the high-resolution peat layer, the peatland lake layer, and layers of field cores. In addition, other fundamental GIS layers are also included, such as administrative boundaries, WSL boundaries, and drainage networks. It is freely available for scientific use from the Arctic System Science Data Coordination Center (ADCC) in Boulder, Colorado (http://arcss.colorado.edu/data/arcss131.html).

8. Concluding Remarks

[34] Our detailed, GIS-based inventory of nearly 10,000 west Siberian peatlands finds that the WSL peat carbon pool contains at least 70.21 Pg C, a substantially larger amount than previously thought. Previous estimates range from 40 to 55 Pg C. One reason for the observed increase is inclusion

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of new data from ongoing Russian field survey programs, and our extension of coverage beyond that of earlier inventories. Furthermore, our revised estimate is considered to be a minimum value, as (1) the Russian data surveys compiled in this study do not consider thin peats (<50 cm); (2) the Russian field measurements may slightly underestimate peat bulk density and LOI as compared with our own field data; and (3) we assume only 52% peat organic carbon percentage in our calculations. However, even with these conservative assumptions, the WSL peatlands represent substantial carbon pool at 70.21 Pg C, about 3.2% of all terrestrial carbon (2190 Pg C [*Houghton et al.*, 1996]).

[35] The WSL peat carbon pool is bisected at approximately 63°N by the Sibirskie Uvaly Hills. The northern pool contains about one third of the total WSL peatland area but only ~24% of the carbon pool. The more significant southern pool contains about 395,000 km^2 of peatlands, comprising ~76% of the total carbon pool. Maximum carbon density is found in the south between 57°N and 61°N, with 44.41 Pg C contained in just 295,824 km^2 of peatland area, yielding a mean carbon density of 150 kgC/m^2.

[36] GIS technologies allow peatland distribution, physical properties, and carbon content to be inventoried and analyzed to the full resolution allowed by the input data. The spatially explicit inventory presented here represents compilation of ~30,000 unpublished Russian measurements of peatland depth, area, bulk density, and ash content. Validation is obtained using our own core, depth, and ground-penetrating radar data, published observations, and high-resolution visible/near-infrared satellite imagery. Incomplete or missing records are modeled using interpolation and geostatistics routines. The patch-based peat carbon pool estimation model presented here resolves peat carbon stocks with a spatial resolution 3 orders of magnitude higher than homogeneous or region-based models. In addition, the patch-based model is data driven and is therefore more objective than other methods. This approach is limited only by the availability of accurate peatland maps or satellite images, and field and laboratory measurements of physical peat properties. The derived GIS database described in this paper represents a substantial advance in our knowledge of the size, location, shape, distribution, and physical properties of west Siberian peatlands.

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References

Botch, M. S., and V. V. Masing (1983), Mire ecosystems in the USSR, in *Ecosystems of the World*, vol. 4B, *Mires: Swamp, Bog, Fen and Moor*, edited by A. P. Gore, pp. 95–152, Elsevier, New York.

Botch, M. S., K. I. Kobak, T. S. Vinson, and T. P. Kolchugina (1995), Carbon pools and accumulation in peatlands of the Former Soviet Union, *Global Biogeochem. Cycles*, *9*(1), 37–46.

Davydova, M. I., and E. M. Rachkovskaya (1990), *Physical Geography of the USSR* (in Russian), vol. 2, 304 pp., Prosveschenie, Moscow.

Dubinin, P., A. Kalashnikov, L. C. Smith, G. M. McDonald, K. V. Kremenetski, and A. A. Velichko (2000), The western Siberian peatbogs ground penetrating radar investigation results, paper presented at Georadar in Russia 2000 Conference, Moscow State Univ., Moscow.

Efremov, S. P., and T. T. Efremova (2001), Present stocks of peat and organic carbon in bog ecosystems of west Siberia, in *Carbon Storage and Atmospheric Exchange by West Siberian Peatlands*, edited by W. Bleuten and E. D. Lapshina, pp. 73–78, Utrecht Univ., Utrecht, Netherlands.

Efremova, T. T., S. P. Efremov, and N. V. Melent'eva (1997), The reserves and forms of carbon compounds in bog ecosystems of Russia (in Russia), *Pochvovedenie*, *12*, 1470–1471.

Forman, S. L., Ó. Ingólfsson, V. Gataullin, W. Manley, and H. Lokrantz (2002), Late Quaternary stratigraphy, glacial limits, and paleoenvironments of the Marresale area, western Yamal peninsula, Russia, *Quat. Res.*, *57*(3), 355–370.

Freeman, C., C. D. Evans, D. T. Monteith, B. Reynolds, and N. Fenner (2001), Export of organic carbon from peat soils, *Nature*, *412*, 785.

Fridland, V. M. (Ed.) (1988), Pochvennaya karta RSFSR (Soil map of the Russian Federation), scale 1:2,500,000, GUGK, Moscow.

Gorham, E. (1991), Northern peatlands: Role in the carbon cycle and probable responses to climatic warming, *Ecol. Appl.*, *1*(2), 182–195.

Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (1996), *Climate Change 1995: The Science of Climate Change*, 572 pp., Cambridge Univ. Press, New York.

Johnston, K., J. M. Ver Hoef, K. Krivoruchko, and N. Lucas (2001), *Using ArcGIS Geostatistical Analyst*, 300 pp., Environ. Syst. Res. Inst., Redlands, Calif.

Kivinen, E., and P. Pakarinen (1981), Geographical distribution of peat resources and major peatland complex types in the world, *Ann. Acad. Sci. Fenn., Ser. A*, *132*, 1–28.

Kremenetski, K. V., A. A. Velichko, O. K. Borisova, G. MacDonald, L. C. Smith, K. E. Frey, and L. A. Orlova (2003), Peatlands of the Western Siberian Lowlands: Current knowledge on zonation, carbon content and late Quaternary history, *Quat. Sci. Rev.*, *22*, 703–723.

Lapshina, E. D., and N. N. Pologova (2001), Carbon accumulation, in *Carbon Storage and Atmospheric Exchange by West Siberian Peatlands*, edited by W. Bleuten and E. D. Lapshina, pp. 50–72, Tomsk, Utrecht, Netherlands.

Markov, V. D. (Ed.) (1971), Karta torfyanykh mestorozhdeniy Zapadno-Sibirskoi ravniny (Map of peat deposits of West Siberian lowland), scale 1:1,000,000, Geoltorfrazvedka, Moscow.

Matukhin, R. G. (Ed.) (1997), Karta torfyanykh mestorozhdeniy Krasnoyarskogo kraya (Map of peat deposits of Krasnoyarsk Region), Ministerstvo Prirodnykh resoursov Rossiiskoi Federatsii. Sibirski NII geologii, Geophyziki i Mineralnogo Syrya, scale 1:1,000,000, Novosibirsk, Russia.

Matukhin, R. G., and V. P. Danilov (Eds.) (2000), Karta torfyanykh mestorozhdeniy Zapadnoi Sibiri (Map of peat deposits of West Siberia), Ministerstvo Prirodnykh resoursov Rossiiskoi Federatsii, Sibirski NII geologii, Geophyziki i Mineralnogo Syrya, scale 1:1,000,000, Novosibirsk, Russia.

Neustadt, M. I. (1971), The world natural phenomenon—Bogs of the West Siberian Lowland (in Russian), *Izv. Akad. Nauk SSSR, Ser. Geograf.*, *1*, 21–34.

Oechel, W. C., and G. L. Vourlitis (1994), The effects of climate change on land-atmosphere feedbacks in Arctic tundra regions, *Trends Ecol. Evol.*, *9*, 324–329.

Romanova, E. A., R. T. Bybina, E. F. Golitsyna, G. M. Ivanova, L. I. Usova, and L. G. Trushnikova (1977), Tipologicheskaya karta bolot Zapadno-Sibirskoi ravniny (Typological map of wetlands of West Siberian Lowland), scale 1:2,500,000, GUGK, Moscow.

Roulet, N. T. (2000), Peatlands, carbon storage, greenhouse gases, and the Kyoto protocol: Prospects and significance for Canada, *Wetlands*, *20*(4), 605–615.

Sabo, E. D., Y. N. Ivanov, and D. A. Shatillo (1981), *Handbook of a Specialist in Hydromelioration of Forest* (in Russian), 200 pp., Lesnaya Promyshlennost, Moscow.

Smith, L. C., G. M. MacDonald, K. E. Frey, A. Velichko, K. Kremenetski, O. Borisova, P. Dubinin, and R. R. Forster (2000), U.S.-Russian venture probes Siberian peatlands' sensitivity to climate, *Eos Trans. AGU*, *81*(43), 497, 503–504.

Smith, L. C., G. M. MacDonald, A. A. Velichko, D. W. Beilman, O. K. Borisova, K. E. Frey, K. V. Kremenetski, and Y. Sheng (2004), Siberian peatlands a net carbon sink and global methane source since the Early Holocene, *Science*, *303*, 353–356.

Stolbovoi, V. (2002), Carbon in Russian soils, *Clim. Change*, *55*(1–2), 131–156.

Tarnocai, C. (1998), The amount of organic carbon in various soil orders and ecological provinces in Canada, in *Soil Processes and the Carbon Cycle*, vol. 2, edited by R. Lalet et al., pp. 81–92, CRC, Boca Raton, Fla.

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Tiuremnov, S. N. (1976), *Peat Deposits I* (in Russian), 487 pp., Nedra, Moscow.

Turunen, J., T. Tahvanainen, K. Tolonen, and A. Pitkanen (2001), Carbon accumulation in west Siberian mires, Russia, *Global Biogeochem. Cycles*, *15*(2), 285–296.

Vitt, D. H., L. A. Halsey, I. E. Bauer, and C. Campbell (2000), Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene, *Can. J. Earth Sci.*, *37*, 683–693.

Vompersky, S. E., A. I. Ivanova, O. P. Tsyganova, N. A. Valiaeva, T. V. Glukhova, F. I. Dubinin, and L. G. Markelova (1994), Boggy soils and bogs in Russia and their carbon pool (in Russian), *Pochvovedenie*, *12*, 17–25.

Vompersky, S. E., O. P. Tsyganova, A. G. Kovalev, T. V. Glukhova, and N. A. Valyaeva (1999), Zabolochennost territorii Rossii kak factor svyazyvaniya atmosfernogo ugleroda (in Russian), in *Global Changes of Environment and Climate*, edited by G. A. Zavarzin, pp. 124–145, Min. of Sci. and Technol. of the Russ. Fed., Moscow.

Woodwell, G. M., F. T. Mackenzie, R. A. Houghton, M. Apps, E. Gorham, and E. Davidson (1998), Biotic feedbacks in the warming of the earth, *Clim. Change*, *40*, 494–518.

Yefremov, S. P., and T. T. Yefremova (2001), Stocks and forms of deposited carbon and nitrogen in bog ecosystems of west Siberia, in *West Siberian Peatlands and Carbon Cycle: Past and Present*, edited by S. V. Vasiliev, A. A. Titlyanova, and A. A. Velichko, pp. 148–151, Agenstvo Sibprint, Novosibirsk, Russia.

Zoltai, S. C., and F. C. Pollett (1983), Wetlands in Canada: Their classification, distribution, and use, in *Ecosystems of the World*, vol. 4B, *Mires: Swamp, Bog, Fen and Moor*, edited by A. P. Gore, pp. 245–268, Elsevier, New York.

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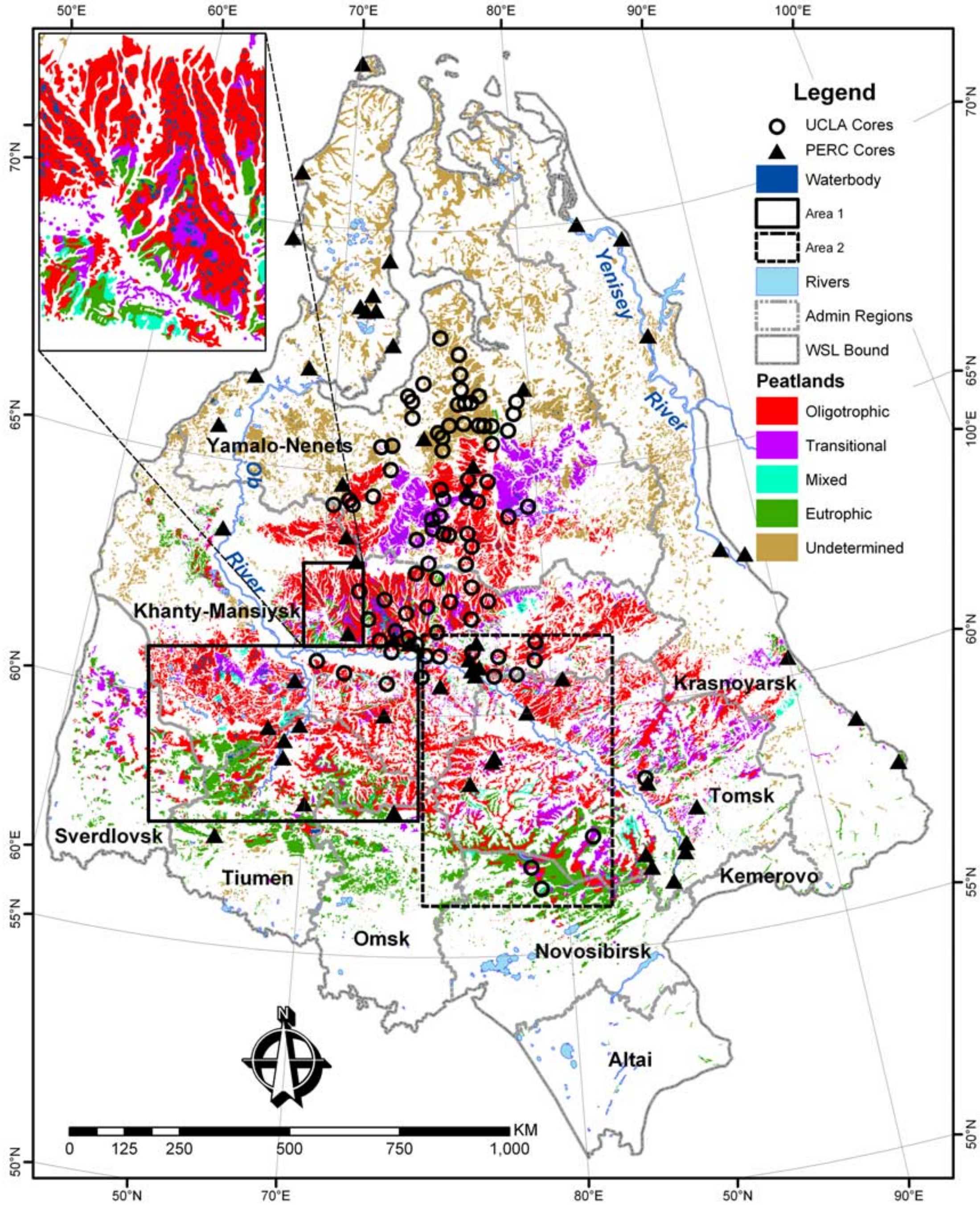

Figure 1. GIS database of WSL peatlands, featuring a detailed peat layer and a peatland lake layer. The peat layer was compiled from the 2000 Novosibirsk peat maps, the 1971 Geoltorfrazvedka peat maps, and the 1977 wetland map. The layer contains 9,691 peat patches, composed of 12,401 polygons showing peat type (oligotrophic, transitional, eutrophic, mixed, or undetermined). Each patch has attribute data: peat area (A), mean depth (D_m), mean bulk density (ρ_m), and mean LOI (L_m, loss on ignition). The peatland lake layer contains 2,796 large water bodies within peatlands. The 'Area 1' and 'Area 2' boxes outline the coverage of two RESURS-01 images used for validating the GIS peat layer. Field validation of peat depth and physical properties are provided by UCLA cores (open circles) and PERC cores (black triangles).

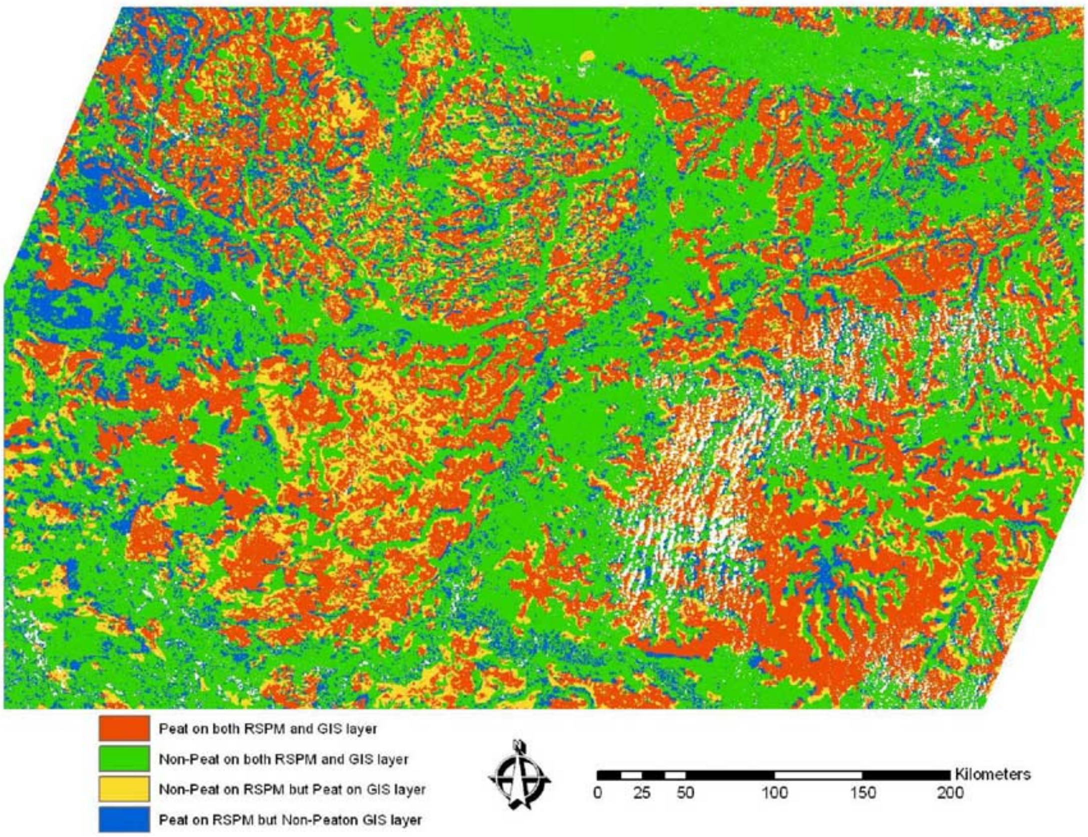

Figure 2. Peatland area validation for Area 1. Overlay of the remotely sensed peat maps (RSPM) with the corresponding portion of the GIS peat layer yields four categories: peat on both maps (red), non-peat on both maps (green), non-peat on RSPM but peat on the GIS peat layer (yellow), and peat on RSPM but non-peat on the GIS peat layer (blue). The red and green colors correspond to agreement, while yellow and blue show disagreement between RSPM and the GIS layer.

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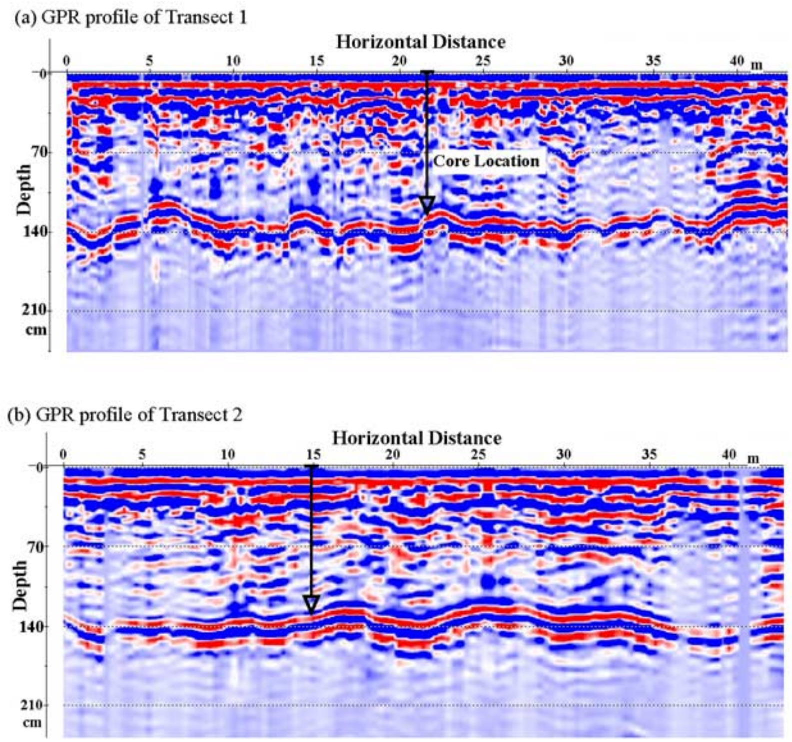

Figure 4. Ground-penetrating radar profiles. Two intersecting 43 m GPR profiles were collected at a UCLA core site (61.546°N, 72.715°E). Profile-averaged depth (1.29 m, $\sigma = 0.06$ m) corresponds well with the single measurement of core depth (1.25 m).

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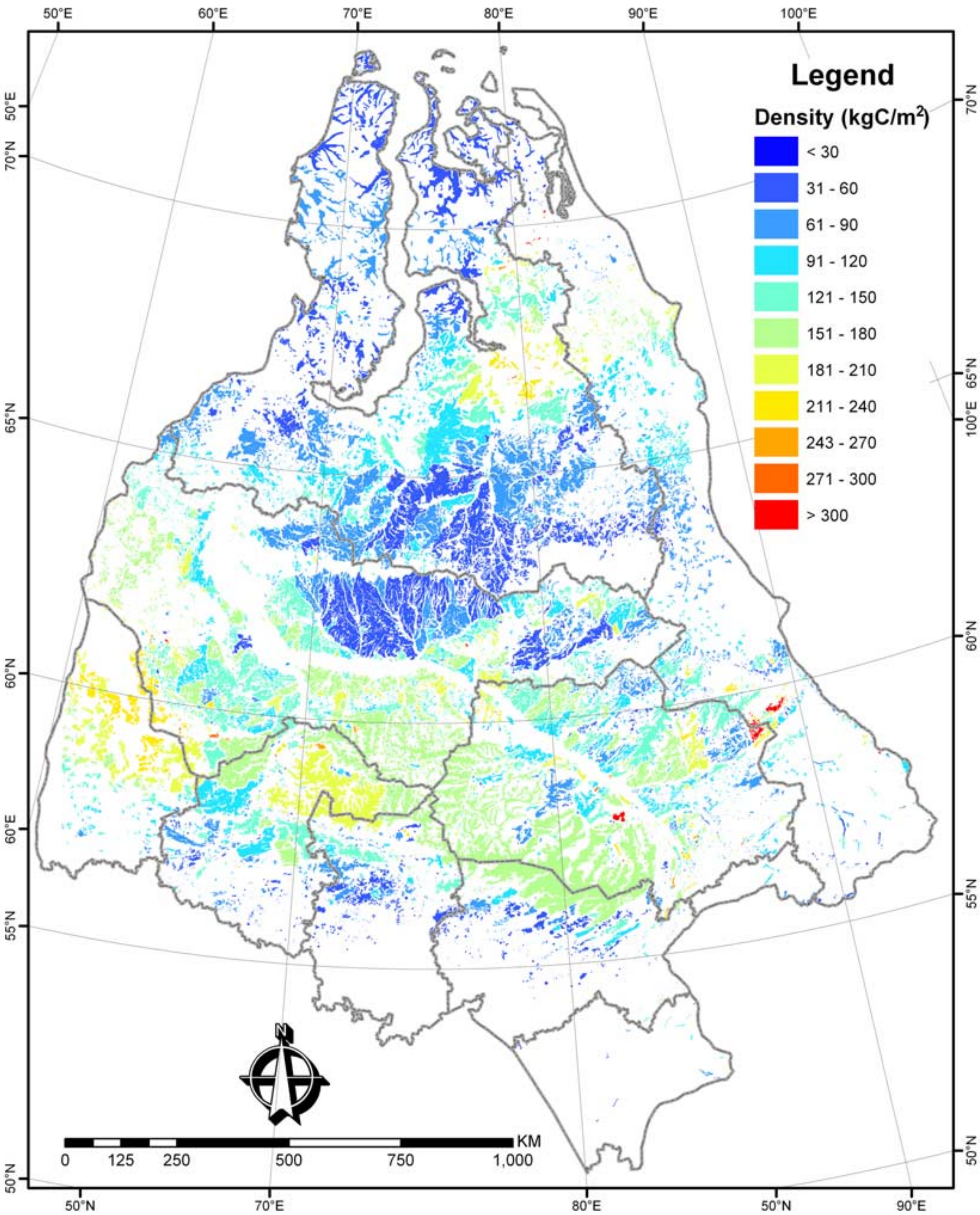

Figure 7. Map of WSL carbon density (carbon per unit area). Higher carbon densities occur in deeper and denser peatlands. Carbon density is greatest near 58°N, but is relatively low near the Sibirskie Uvaly Hills (∼63°N).