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How well do we know northern land cover? Comparison of four global vegetation and wetland products with a new ground-truth database for West Siberia

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How well do we know northern land cover? Comparison of four global vegetation and wetland products with a new ground-truth database for West Siberia

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[1] An unprecedented collection of 2161 geolocated, irregularly spaced field observations of land cover spanning ~10^6 km^2 throughout West Siberia suggests that currently available land cover classification products are remarkably poor indicators of vegetation type and water body extent in this northern wetland environment. The ground-truth data are compared with (1) the Global Land Cover Characteristics database derived from Advanced Very High Resolution Radiometer data (GLCC.AVHRR), (2) the Global Land Cover Classification derived from Moderate Resolution Imaging Spectroradiometer data (GLCC.MODIS), (3) the Global Lakes and Wetlands Database (GLWD), and (4) the West Siberian Lowland Peatland Database (WSLPD) using: (1) all land cover categories and (2) permanent wetland and water body categories only. Overall agreement with ground observations of land cover is only 21% for the GLCC.AVHRR database and 11% for the GLCC.MODIS database. However, at a much broader scale (one degree of latitude) there is improved qualitative agreement between vegetation classes, with some notable exceptions: (1) at low latitudes (~54°N–58°N), both the GLCC.AVHRR and GLCC.MODIS databases underestimate woody savannas in favor of croplands; (2) at midlatitudes (~58°N–64°N), the GLCC.AVHRR database underestimates evergreen needleleaf forest in favor of mixed forest; and (3) at high latitudes (~64°N–68°N), both the GLCC.AVHRR and GLCC.MODIS databases underestimate deciduous needleleaf forest in favor of woody savannas or open shrublands, respectively. It is clear that all four data databases significantly underestimate permanent wetlands and water bodies, although those specifically developed for this purpose (GLWD and WSPLD) perform better than the more widely used, multiclass land cover products. For permanent wetlands, agreement with our ground data is only 2% for GLCC.MODIS, 23% for GLCC.AVHRR, 45% for GLWD and 56% for WSLPD. Agreement with open water bodies is even poorer (0–5%). These results raise into question the efficacy of incorporating currently available land cover products into terrestrial ecosystem models in northern wetland environments.

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1. Introduction

[2] To correctly model biophysical aspects of global change, it is critical to begin with an accurate baseline estimate of the vegetation distribution of a region. To this end, land cover classification maps based on satellite imagery are commonly used in terrestrial ecosystem models to predict the potential impacts of climate change on land-atmosphere exchanges of energy, water, carbon and greenhouse gases [e.g., *Nemani and Running*, 1996; *Lucas and Curran*, 1999; *Markon and Peterson*, 2002; *Cox et al.*, 2004; *Krinner et al.*, 2005]. Furthermore, an accurate assessment of the extent of wetlands and water bodies is critical in studies of hydrology, water resources, ecology, land-atmosphere interactions and trace gas emissions [e.g., *Kling et al.*, 1991; *Vörösmarty et al.*, 1997; *Mitsch and Gosselink*, 2000; *Malcom et al.*, 2002]. Unfortunately, however, most land cover maps based on satellite imagery are notoriously erroneous in wetland areas (J. M. Melack, personal communication, 2004). This is problematic for modeling of current land-atmosphere exchange and also

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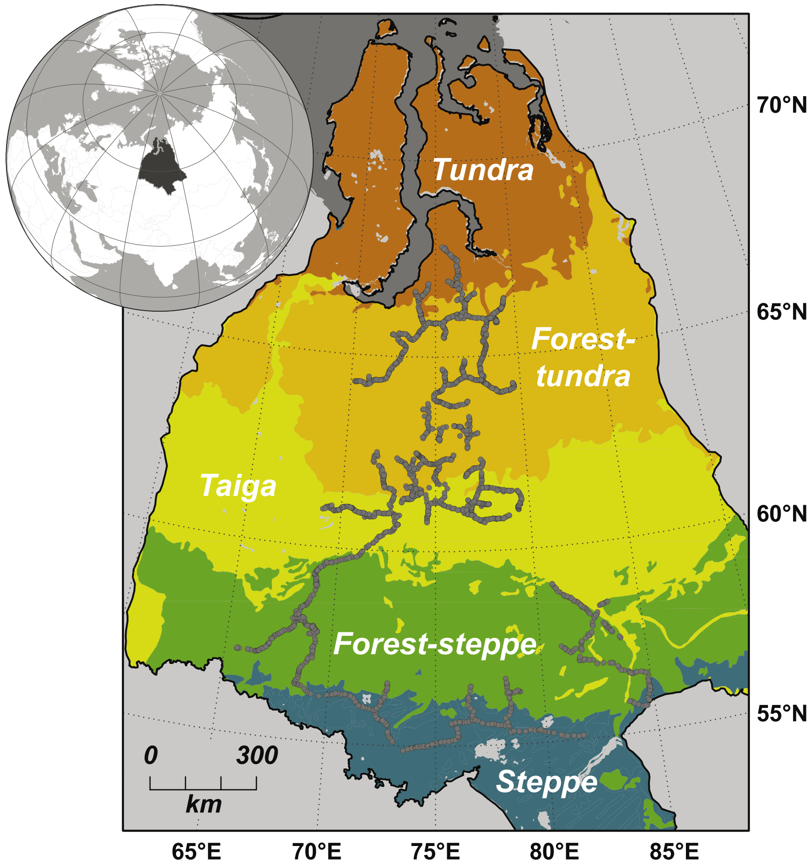

Figure 1. Locations of the 2161 ground-truth observations of land cover distributed throughout the $\sim 10^6$ km^2 study region in West Siberia. Field transects cover 54°N–68°N in latitude and all five bioclimatic zones of the region [*Stolbovoi and McCallum*, 2002].

future climate scenarios, in which the response of northern vegetation and surface hydrology has the potential to trigger certain feedbacks to regional and global climate [e.g., *Chapin et al.*, 2005; *Hinzman et al.*, 2005].

[3] The problem is particularly acute in the vast lowlands of West Siberia, a region spanning $\sim 2.6 \times 10^6$ km^2 and five vegetation biomes [*Stolbovoi and McCallum*, 2002] (Figure 1). The region also contains extensive lakes and wetlands [*Sheng et al.*, 2004; *Smith et al.*, 2005]. Cool temperatures, poor drainage and waterlogged conditions have caused accumulation of $\sim$70 Pg C of organic peat carbon in these wetlands over the past $\sim$11,000 years, making them a Holocene carbon sink of global significance [*Kremenetski et al.*, 2003; *Sheng et al.*, 2004; *Smith et al.*, 2004]. Furthermore, the region encompasses a broad range of land cover types separated by the northern treeline, with land cover consisting primarily of prostrate vegetation north of treeline and dense boreal forest south of treeline [*MacDonald et al.*, 2000; *MacDonald*, 2002; *Esper and Schweingruber*, 2004]. If perturbed by climate warming, both peatlands and forests have the potential to instigate several important feedback mechanisms. Decreased wetness in peatlands would reduce methane emissions but potentially cause them to become a significant source of atmospheric CO_2 through enhanced aerobic decomposition [*Gorham*, 1991; *Oechel et al.*, 1993; *Gorham*, 1994]. Warming may also lower surface albedo through the northward expansion of boreal forest, causing greater surface absorption of solar radiation with a resulting significant positive feedback to warming [e.g., *Chapin et al.*, 1997; *Shaver et al.*, 2000; *Chapin et al.*, 2005]. Increases in shrub cover can exert a similar effect [e.g., *Sturm et al.*, 2001], and such expansions are not unprecedented in Eurasia [*MacDonald et al.*, 1993].

[4] From north to south, West Siberia comprises tundra, forest-tundra, taiga, forest-steppe and steppe bioclimatic zones (Figure 1). The northernmost tundra zone contains prostrate vegetation consisting of shrubs, dwarf shrubs, grasses, sedges, mosses and lichens. The forest-tundra zone contains tundra vegetation with interspersed stands of birch (*Betula pendula, Betula pubescens*), spruce (*Picea obovata*) and larch (*Larix siberica*) [*Bleuten and Lapshina*, 2001; *Kremenetski et al.*, 2003]. The taiga (or boreal forest) zone grades from a northern dominance of *L. siberica* to southern dominance of *P. obovata, Betula alba*, pine (*Pinus sibirica, Pinus sylvestris*), and fir (*Abies sibirica*) [*Bleuten and Lapshina*, 2001; *Shahgedanova*, 2002]. In the most southern areas, the forest-steppe zone includes scattered stands of *B. pendula, B. pubescens* and mixed poplar-birch communities, whereas the steppe zone consists primarily of several species of herbs and grasses [*Bleuten and Lapshina*, 2001;

Shahgedanova, 2002; *Kremenetski et al.*, 2003]. The forest-tundra, taiga and forest-steppe zone also contains peatlands and forested peatlands, with mosses, grasses, sedges, shrubs and small scattered species of larch, pine and birch. These peatlands cover nearly 600,000 km^2 but are bimodal in their areal distribution, separated by the Sibirskie Uvaly Hills (at ~63°N) with ~1/3 of the total peatland area northward of this boundary and ~2/3 southward [*Sheng et al.*, 2004]. Open water bodies are numerous throughout the region and in some areas cover more than 50% of the total surface area [*Kremenetski et al.*, 2003].

[5] In this study, we present an unprecedented new database of 2161 field-based observations of land cover distributed throughout the $\sim 2.6 \times 10^6$ km^2 West Siberian region (Figure 1). The field data are compared with four land cover and wetland classification products: (1) the Global Land Cover Characteristics database derived from Advanced Very High Resolution Radiometer data (GLCC.AVHRR) [*Loveland et al.*, 2000; *U.S. Geological Survey*, 2004]; (2) the Global Land Cover Classification derived from Moderate Resolution Imaging Spectroradiometer data (GLCC.MODIS) [*Friedl et al.*, 2002]; (3) the Global Lakes and Wetlands Database (GLWD) [*Lehner and Döll*, 2004]; and (4) the West Siberian Lowland Peatland Database (WSLPD) [*Sheng et al.*, 2004]. Utilizing a Geographic Information System (GIS), we compile these databases in order to compare: (1) the GLCC.AVHRR, GLCC.MODIS and field databases using all categories of the International Geosphere-Biosphere Programme (IGBP) legend [*Belward*, 1996]; and (2) the GLCC.AVHRR, GLCC.MODIS, GLWD, WSLPD and field products using "permanent wetlands" and "water bodies" categories only. In all cases, our field data are assumed to be "ground truth" and therefore correct. The field data are compared with the other databases at two spatial scales: (1) fine resolution, in which the 2161 field observations are compared individually with their corresponding grid cell values in the four land cover and wetland databases; and (2) coarse resolution, in which the field and corresponding grid cell values are binned within one-degree latitudinal bands. Taken together, these analyses provide both quantitative and qualitative assessment of the strengths and limitations of these widely used land cover and wetland products.

2. Data and Methods

2.1. Field Database

[6] Field campaigns during July and August of 1999, 2000 and 2001 yielded 2161 land cover observation points throughout West Siberia, distributed irregularly over an area of $\sim 10^6$ km^2 (Figure 1). These measurements were carried out as a part of a broader study examining the sensitivity of the region's wetlands to climate [*Smith et al.*, 2000]. Observations of land cover were made either while driving or when stopped at field sites. For each observation, the geographic coordinates were recorded using the 12-channel Garmin eTrex Venture handheld Global Positioning System (GPS) device with a nominal accuracy of <15 m (although accuracies were typically lower at ~5–10 m). A general characterization of the land cover at each location was assessed visually from a single point over a ~1 km^2 surrounding land surface area, using one of the 253 land cover classes defined by the Eurasia Seasonal Land Cover Regions (ESLCR) legend [*U.S. Geological Survey*, 2004]. These data were recorded only where the land cover appeared relatively homogenous and could be seen with expansive views over a large spatial scale (i.e., greater than ~1 km^2). In general, this was easily accomplished owing to the remarkably flat landscape throughout West Siberia (e.g., Figure 2). If there were any questions of the homogeneity of the land cover, large portions of the ~1 km^2 land surface area were traversed (e.g., to distinguish wetland from grassland). While individual observations were sampled randomly in space and time, they naturally congregate along existing road networks (and hence, are not purely random in space). Nevertheless, the breadth of the existing road infrastructure allowed good spatial coverage throughout the study area, including all five bioclimatic zones (Figure 1). For analysis purposes, the field database was further simplified from the ESLCR legend into one of the 17 land cover classes defined by the IGBP legend [*Belward*, 1996]. This simplification was performed using a legend conversion also provided by the U.S. Geological Survey (USGS) (http://edcsns17. cr.usgs.gov/glcc/ealcdbtab2_0.txt). The final ground-truth database therefore conforms with the 17-class IGBP legend as follows: (1) evergreen needleleaf forest, (2) evergreen broadleaf forest, (3) deciduous needleleaf forest, (4) deciduous broadleaf forest, (5) mixed forest, (6) closed shrublands, (7) open shrublands, (8) woody savannas, (9) savannas, (10) grasslands, (11) permanent wetlands, (12) croplands, (13) urban and built up, (14) cropland/natural vegetation mosaic, (15) snow and ice, (16) barren or sparsely vegetated and (17) water bodies. Examples of these land cover classes as seen in the field are shown in Figure 2. The final ground-truth data set used in this study thus consists of 2161 GPS coordinates distributed throughout the region (Figure 1), each with an associated IGBP land cover classification. The full data set, available in both the ESLCR and IGBP legends, is provided as auxiliary material[1].

2.2. Digital Databases

[7] The GLCC.AVHRR database [*Loveland et al.*, 2000] is based on AVHRR data acquired from April 1992 through March 1993 and has a 1-km nominal spatial resolution. This database is available from the USGS Earth Resources Observation & Science (EROS) data center in Sioux Falls, South Dakota (http://edcsns17.cr.usgs.gov/glcc/) [*USGS*, 2004]. In this study, we utilize the Eurasia Land Cover Characteristics Data Base (version 2.0), that portion of the GLCC.AVHRR database developed with particular consideration for the salient geographic aspects of the Eurasian continent. Described succinctly, this database is created as follows: (1) Normalized Difference Vegetation Index (NDVI) composites are created from the composite AVHRR data; (2) NDVI composites are classified into land cover clusters using an algorithm similar to the K-Means

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gb/2006gb002706.

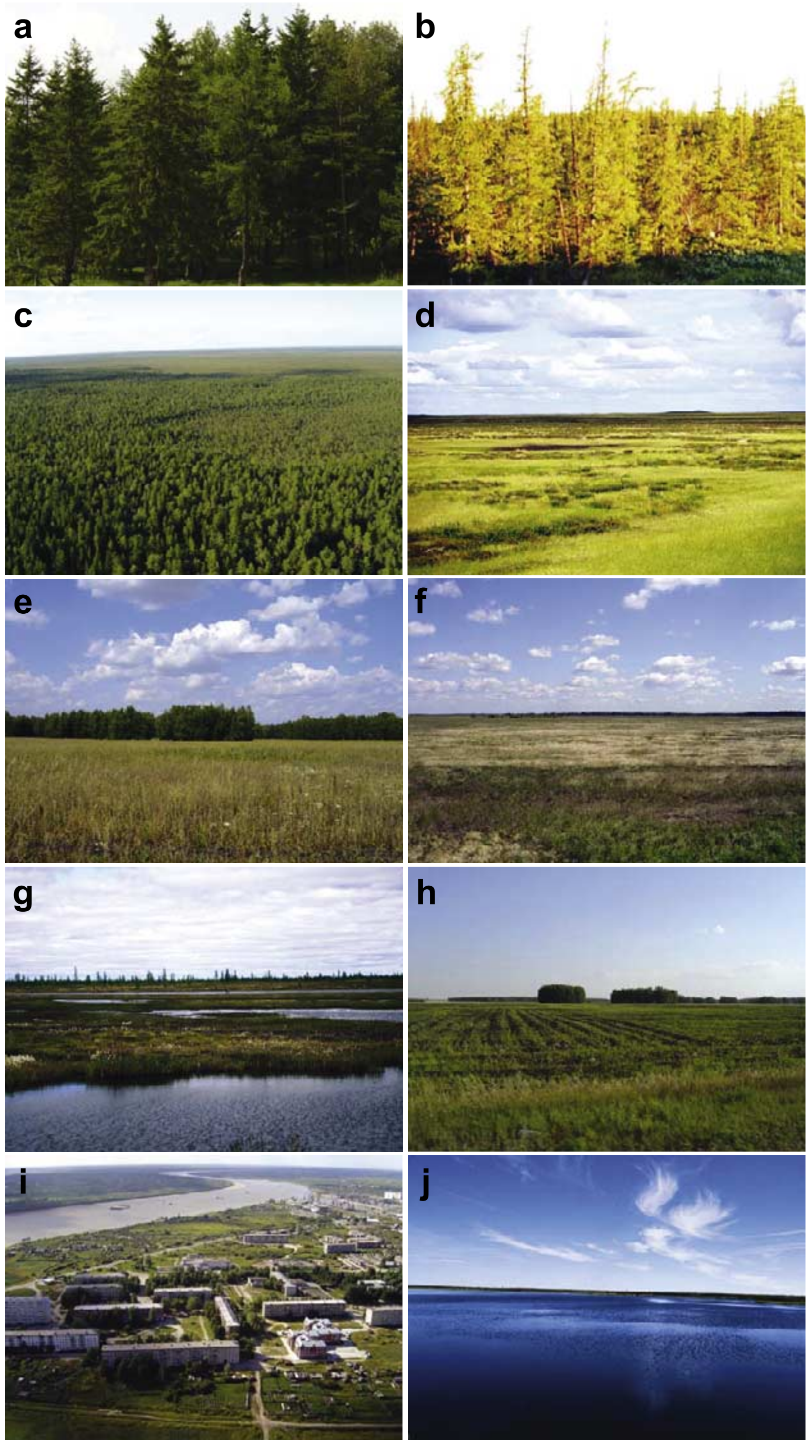

Figure 2. Typical International Geosphere-Biosphere Programme (IGBP) land cover categories of West Siberia: (a) evergreen needleleaf forest, (b) deciduous needleleaf forest, (c) mixed forest, (d) open shrublands, (e) woody savannas, (f) grasslands, (g) permanent wetlands, (h) croplands, (i) urban and built up, and (j) water bodies. Only those land cover categories representing at least 1% of our total field observations are shown, which excludes evergreen broadleaf forest, deciduous broadleaf forest, closed shrublands, savannas, cropland/natural vegetation mosaic, snow and ice, and barren or sparsely vegetated.

classifier; and (3) land cover types are assigned to each of the clusters [*Loveland et al.*, 2000]. The resulting land cover product is scaled using several different legends, including the 253-category ESLCR legend and the 17-category IGBP legend. Here we utilize the IGBP legend in order to maintain consistency between databases.

[8] The GLCC.MODIS database utilized here is developed by the Boston University Department of Geography and Center for Remote Sensing (http://geography.bu.edu/landcover/) [*Friedl et al.*, 2002]. The data product is based on MODIS data acquired from 15 October 2000 through 15 October 2001 (version 2000289 V003), has a 1-km nominal spatial resolution, and was produced using a supervised classification approach. Training sites were developed by analyzing high-resolution (e.g., Landsat TM) imagery in conjunction with ancillary data, with the classification produced using a decision tree algorithm combined with a technique for improving classification accuracies known as boosting [*Friedl et al.*, 2002]. The resulting classification is available with a variety of legends. As before, we utilize the IGBP legend to maintain consistency with the GLCC.AVHRR and field databases.

[9] The GLWD is a global database representing the extent of lakes, permanent open water bodies and wetlands compiled from a variety of existing maps and databases (http://www.wwfus.org/science/data.cfm/) [*Lehner and Döll*, 2004]. The GLWD was primarily developed from a compilation of six preexisting vector and raster databases including (1) the Mullard Space Science Laboratory Global Lakes Database [*Birkett and Mason*, 1995]; (2) the Data Set of Large Reservoirs [*Vörösmarty et al.*, 1997]; (3) the Digital Chart of the World [*Environmental Systems Research Institute*, 1993]; (4) the ArcWorld 1:3M Data Set [*Environmental Systems Research Institute*, 1992]; (5) Wetlands Map of the World Conservation Monitoring Center [*Dugan*, 1993; *World Conservation Monitoring Centre*, 1993]; and (6) the USGS Global Land Cover Characteristics Database [*Loveland et al.*, 2000], the same database (GLCC.AVHRR) described above. The Level 1 (GLWD-1) database represents the largest lakes (area $\geq$ 50 km^2) and reservoirs (storage $\geq$ 0.5 km^3) worldwide; the Level 2 (GLWD-2) database represents the areal extents of smaller lakes, reservoirs and rivers (area $\geq$ 0.1 km^2) worldwide. In this study, we utilize the Level 3 database (GLWD-3), which is 30-second resolution raster data combining the GLWD-1 and GLWD-2 databases and additionally includes the extent of wetlands.

[10] The WSLPD is a vector-based GIS data collection that presents detailed physical characteristics of nearly 10,000 individual peatlands (i.e., wetlands) throughout West Siberia and is based on field and map data published by the Russian Federation Geological Survey (1:1M scale) and State Hydrological Institute (1:2.5M scale), previously published peat depth measurements, and peat depth measurements obtained through field campaigns in 1999, 2000 and 2001 (http://arcss.colorado.edu/data/arcss131.html/) [*Sheng et al.*, 2004]. The WSLPD further includes: (1) open water bodies within peatlands digitized from the same Russian maps described above; and (2) drainage networks and open water bodies extracted from the Digital Chart of the World [*Environmental Systems Research Institute*, 1993].

2.3. Database Intercomparison

[11] All of the above five geolocated databases were compared with one another within the West Siberian region ($\sim$2.6 $\times$ 10^6 km^2; Figure 1) using a Lambert Azimuthal Equal Area map projection in the ESRI® ArcGIS™ v. 9.1 GIS. Agreement between the GLCC.AVHRR, GLCC.MODIS and field databases was determined in the GIS using all 17 categories of the IGBP legend. For assessment of wetlands and open water bodies, the GLCC.AVHRR, GLCC.MODIS and field databases were further simplified to extract only those areas defined as permanent wetlands (category 11) or water bodies (category 17) in the IGBP legend, allowing direct comparison with the GLWD and WSLPD products. To summarize, the database comparisons made in this study are: (1) the GLCC.AVHRR, GLCC.MODIS and field databases delineating all 17 land cover categories in the IGBP legend; and (2) the GLCC.AVHRR, GLCC.MODIS, GLWD, WSLPD and field databases delineating only two categories (permanent wetlands and water bodies), with much of the land surface area within the region classifying as neither category. Furthermore, to investigate the latitudinal distribution of all IGBP categories, it was determined what the 2161 geolocated field observation points were classified as in each of the GLCC.AVHRR, GLCC.MODIS, GLWD and WSLPD data products. The resulting five separate collections of 2161 data values were then binned into one-degree bands, enabling broad-scale latitudinal comparisons between all five data sets.

[12] Assessment of the overall accuracy of each of these databases is presented using error matrices and Cohen's Kappa [e.g., *Jensen*, 1996]. Kappa can be used as a measure of whether values presented in an error matrix represent a result significantly better than random. The Kappa Coefficient ($\hat{\kappa}$) can be defined as

$$\hat{\kappa} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+}\cdot x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+}\cdot x_{+i})}, \quad (1)$$

where r is the number of rows in the error matrix; x_{ii} is the number of observations in row i and column i (on the major diagonal); x_{i+} is the total of observations in row i; x_{+i} is the total of observations in column i; and N is the total number of observations included in the matrix. A $\hat{\kappa}$ of 0 suggests that a given classification is no better than a random assignment of pixels, whereas a $\hat{\kappa}$ of 1 is the ideal case.

3. Results

3.1. Fine-Scale Evaluation of Land Cover

[13] West Siberian land cover as represented by the GLCC.AVHRR and GLCC.MODIS land cover databases

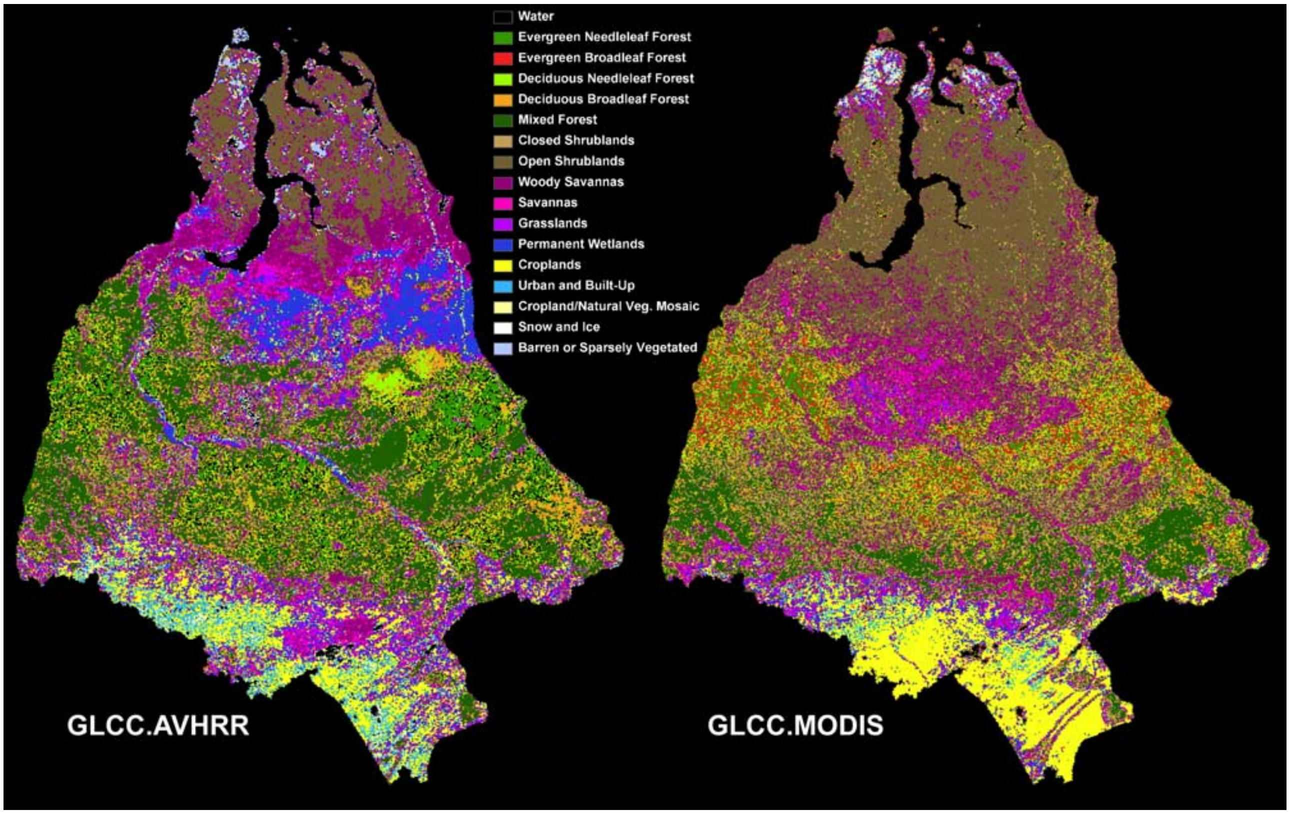

Figure 3. Land cover of West Siberia as classified by the Global Land Cover Characteristics database derived from Advanced Very High Resolution Radiometer data (GLCC.AVHRR) and the Global Land Cover Classification database derived from Moderate Resolution Imaging Spectroradiometer data (GLCC.MODIS). All classes shown conform to the 17 categories of the IGBP legend.

is shown in Figure 3. Visual inspection reveals that despite some general similarities (open shrublands at northern latitudes; mixed forest at midlatitudes; and croplands at southern latitudes), there is also great disagreement between the two databases. This disagreement is quantified in an error matrix for all 17 IGBP categories (Table 1). Setting aside permanent wetlands and water bodies (discussed in detail in section 3.2), the GLCC.AVHRR classifications are corroborated by GLCC.MODIS most consistently for open shrublands (91%), croplands (61%) and evergreen needleleaf forest (52%), but the agreement declines precipitously for the remaining categories. In turn, the GLCC.MODIS classifications are corroborated by the GLCC.AVHRR classifications most consistently for croplands (64%), mixed forest (55%) and evergreen needleleaf forest (41%). The most predominant class is mixed forest in the GLCC.AVHRR database (32% of the total area), but open shrublands in the GLCC.MODIS database (33% of the total area) (Figure 3 and Table 1). Overall accuracy (i.e., agreement) between the GLCC.MODIS and GLCC.AVHRR land cover products is only 36% for all of West Siberia, with a Kappa Coefficient ($\hat{\kappa}$) of 0.26 (Table 1).

[14] Substantial disagreement is also found between ground-truth observations and both GLCC databases (Tables 2 and 3). In contrast to the remotely sensed products, dominant classes in the 2161 field observations (again, excluding wetlands and water bodies which are described in section 3.2) are mixed forest (22%), evergreen needleleaf forest (19%) or woody savannas (11%) (Tables 2 and 3). Overall, our field observations agree with only 22% of the GLCC.AVHRR database ($\hat{\kappa}$ = 0.07) and 11% of the GLCC.MODIS database ($\hat{\kappa}$ = 0.05) (Tables 2 and 3). Ground-truth matches the GLCC.AVHRR data most consistently for croplands (45%), mixed forest (42%), woody savannas (29%) and open shrublands (26%). For the GLCC.MODIS database, ground-truth matches most consistently for open shrublands (96%), croplands (34%) and grasslands (19%). Better overall agreement is with the GLCC.AVHRR database, in large part because the field observations agree well with GLCC.AVHRR for categories that are most prevalent within the region (e.g., 42% of mixed forest and 23% of permanent wetlands, two categories that together comprise 48% of our field observations; in contrast, field observations agree with only 2% of each of these categories in the GLCC.MODIS database) (Tables 2 and 3).

3.2. Fine-Scale Evaluation of Permanent Wetlands and Water Bodies

[15] It is clear that great differences exist between maps of wetlands/open water bodies provided by the GLCC.AVHRR, GLCC.MODIS, GLWD and WSLPD data-

Table 1. Error Matrix Comparing Classifications of the GLCC.MODIS and GLCC.AVHRR Databases Within the Entire West Siberian Region[a]

	GLCC. AVHRR																	
GLCC.MODIS	Evergreen Needleleaf Forest	Evergreen Broadleaf Forest	Deciduous Needleleaf Forest	Deciduous Broadleaf Forest	Mixed Forest	Closed Shrublands	Open Shrublands	Woody Savannas	Savannas	Grasslands	Permanent Wetlands	Croplands	Urban and Built Up	Cropland/ Natural Veg. Mosaic	Snow and Ice	Barren or Sparsely Vegetated	Water Bodies	Row Total
Evergreen needleleaf forest	141249	0	7366	10951	155272	2896	132	6240	5	1781	8617	4142	146	1934	0	0	2168	342900
Evergreen broadleaf forest	3	0	3	3	22	0	0	15	0	2	13	7	0	2	0	0	2	72
Deciduous needleleaf forest	432	0	201	392	1732	103	5	340	0	31	425	554	0	43	0	0	46	4302
Deciduous broadleaf forest	520	0	126	5535	7863	76	4	301	1	12	422	2450	4	169	0	0	133	17616
Mixed forest	76581	0	3074	58300	270988	1342	83	7893	51	311	2806	59049	254	10663	0	0	2692	494087
Closed shrublands	1	0	1	1	10	0	0	0	0	9	5	0	1	0	0	0	2	30
Open shrublands	14684	0	6597	20573	159166	8729	257021	165603	1	12406	147897	9300	148	3581	0	24663	25831	856198
Woody savannas	27973	0	11086	17606	147369	6449	694	17402	8	1986	26526	14829	133	4217	0	10	5140	281427
Savannas	1901	0	634	2372	35096	1354	52	6677	0	506	1959	8620	98	1557	0	0	1039	61865
Grasslands	2417	0	1691	3483	22233	1502	1986	10068	0	3004	13402	9161	120	5131	0	339	2977	77514
Permanent wetlands	1395	0	196	730	20050	1331	109	3734	0	766	7376	318	2	111	0	0	4266	40384
Croplands	4112	0	9046	4962	6366	76	32	40928	1	10173	114	202379	1933	32677	0	0	3303	316103
Urban and built up	291	0	53	74	2197	243	53	487	0	493	383	701	1006	261	0	9	186	6437
Cropland/natural veg. mosaic	276	0	300	1952	2189	14	0	883	1	22	20	18953	51	1664	0	0	139	26465
Snow and ice	4	0	0	7	210	7	0	6	0	0	0	2	0	1	0	0	4	239
Barren or sparsely vegetated	5	0	0	1	21	1	20357	43	0	29	26	7	1	12	0	2685	150	23339
Water bodies	926	0	214	571	4513	442	2960	3603	0	753	4004	1837	67	787	0	918	38173	59769
Column total	272769	0	40589	127510	835297	24566	283487	264225	68	32284	213995	332308	3963	62810	0	28625	86252	2608747
GLCC.AVHRR accuracy	52%	N/A	0%	4%	32%	0%	91%	7%	0%	9%	3%	61%	25%	3%	N/A	9%	44%	
GLCC.MODIS accuracy	41%	0%	5%	31%	55%	0%	30%	6%	0%	4%	18%	64%	16%	6%	0%	12%	64%	
Overall accuracy	36%																	
Kappa coefficient ($\hat{\kappa}$)	0.26																	

[a]Values presented are the number of square kilometers classifying as each of the categories in the two databases (totaling 2.6×10^6 km^2). Overall accuracy between the two classification products is 36% with a Kappa coefficient of 0.26.

Table 2. Error Matrix Comparing Classifications of the Field and GLCC.AVHRR Databases for the 2161 Field Observation Points Within West Siberia[a]

	Field Database																	
GLCC.AVHRR	Evergreen Needleleaf Forest	Evergreen Broadleaf Forest	Deciduous Needleleaf Forest	Deciduous Broadleaf Forest	Mixed Forest	Closed Shrublands	Open Shrublands	Woody Savannas	Savannas	Grasslands	Permanent Wetlands	Croplands	Urban and Built Up	Cropland/ Natural Veg. Mosaic	Snow and Ice	Barren or Sparsely Vegetated	Water Bodies	Column Total
Evergreen needleleaf forest	23	0	0	0	22	0	0	2	0	1	12	0	0	0	0	0	3	63
Evergreen broadleaf forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deciduous needleleaf forest	3	0	0	0	4	0	0	0	0	1	1	0	1	0	0	0	0	10
Deciduous broadleaf forest	23	0	1	0	33	0	0	5	0	4	11	0	3	0	0	1	6	87
Mixed forest	210	0	15	1	200	0	0	21	0	30	250	12	20	0	0	0	9	768
Closed shrublands	5	0	0	0	4	0	0	1	0	0	6	0	1	0	0	0	0	17
Open shrublands	0	0	14	0	14	0	12	1	0	12	30	0	2	0	0	0	2	87
Woody savannas	10	0	50	0	63	0	16	70	0	31	63	2	14	0	0	12	9	340
Savannas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grasslands	29	0	4	0	15	0	14	1	0	6	31	1	3	0	0	2	4	110
Permanent wetlands	87	0	31	0	79	0	4	2	0	10	129	0	14	0	0	0	28	384
Croplands	13	0	0	3	33	0	0	124	0	9	5	20	5	0	0	0	0	212
Urban and built up	1	0	0	2	1	0	0	3	0	1	1	0	5	0	0	0	0	14
Cropland/natural veg. mosaic	3	0	0	0	7	0	0	15	0	4	3	7	2	0	0	0	0	41
Snow and ice	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barren or sparsely vegetated	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Water bodies	1	0	0	0	4	0	0	0	0	2	12	2	3	0	0	0	3	27
Row total	408	0	115	6	480	0	46	245	0	111	554	44	73	0	0	15	64	2161
Field database accuracy	6%	N/A	0%	0%	42%	N/A	26%	29%	N/A	5%	23%	45%	7%	N/A	N/A	0%	5%	
GLCC.AVHRR Accuracy	37%	N/A	0%	0%	26%	0%	14%	21%	N/A	5%	34%	9%	36%	0%	N/A	0%	11%	
Overall accuracy	22%																	
Kappa coefficient ($\hat{\kappa}$)	0.07																	

[a]Overall accuracy between the two databases is 22% with a Kappa coefficient of 0.07.

Table 3. Error Matrix Comparing Classifications of the Field and GLCC.MODIS Databases for the 2161 Field Observation Points Within West Siberia[a]

	Field Database																	
GLCC.MODIS	Evergreen Needleleaf Forest	Evergreen Broadleaf Forest	Deciduous Needleleaf Forest	Deciduous Broadleaf Forest	Mixed Forest	Closed Shrublands	Open Shrublands	Woody Savannas	Savannas	Grasslands	Permanent Wetlands	Croplands	Urban and Built Up	Cropland/ Natural Veg. Mosaic	Snow and Ice	Barren or Sparsely Vegetated	Water Bodies	Column Total
Evergreen needleleaf forest	43	0	1	0	71	0	0	4	0	1	29	0	3	0	0	0	5	157
Evergreen broadleaf forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deciduous needleleaf forest	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2
Deciduous broadleaf forest	2	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	4
Mixed forest	43	0	0	1	87	0	0	22	0	12	27	7	2	0	0	0	1	202
Closed shrublands	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Open shrublands	158	0	91	0	193	0	44	36	0	63	334	4	39	0	0	14	41	1017
Woody savannas	50	0	5	1	50	0	0	6	0	2	43	2	0	0	0	0	4	163
Savannas	24	0	7	0	10	0	0	8	0	8	33	2	2	0	0	0	1	95
Grasslands	53	0	10	1	27	0	1	5	0	21	55	10	8	0	0	1	7	199
Permanent wetlands	4	0	0	0	1	0	0	0	0	0	11	0	0	0	0	0	4	20
Croplands	2	0	0	3	10	0	0	152	0	3	8	15	6	0	0	0	0	199
Urban and built up	25	0	1	0	22	0	1	1	0	0	7	0	10	0	0	0	1	68
Cropland/natural veg. mosaic	0	0	0	0	4	0	0	10	0	0	0	3	0	0	0	0	0	17
Snow and ice	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barren or sparsely vegetated	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
Water bodies	3	0	0	0	2	0	0	1	0	1	6	1	2	0	0	0	0	16
Row total	408	0	115	6	480	0	46	245	0	111	554	44	73	0	0	15	64	2161
Field database accuracy	11%	N/A	0%	0%	18%	N/A	96%	2%	N/A	19%	2%	34%	14%	N/A	N/A	0%	0%	
GLCC.MODIS accuracy	27%	N/A	0%	0%	43%	N/A	4%	4%	0%	11%	55%	8%	15%	0%	N/A	0%	0%	
Overall accuracy	11%																	
Kappa coefficient ($\hat{\kappa}$)	0.05																	

[a]Overall accuracy between the two databases is 11% with a Kappa coefficient of 0.05.

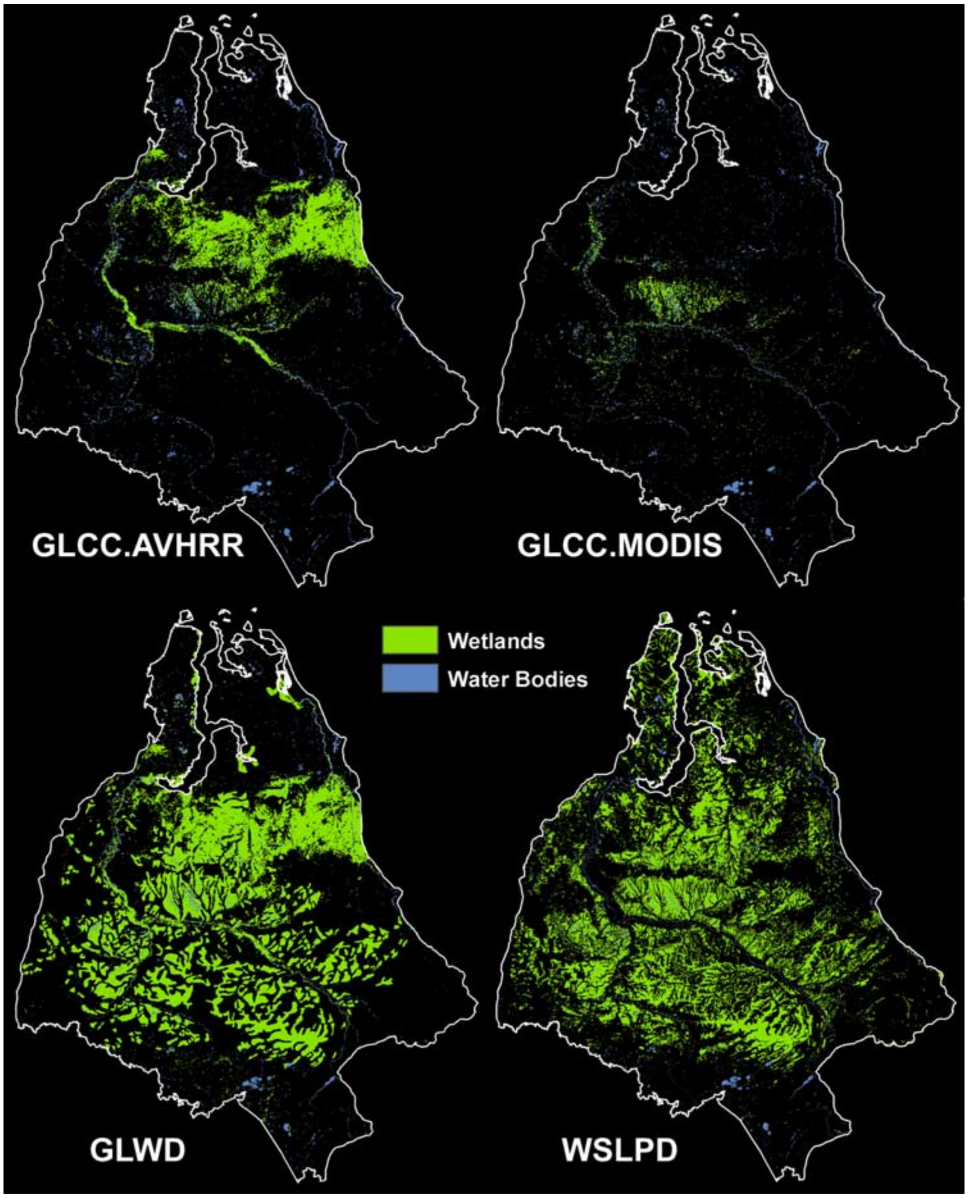

Figure 4. Land area classifying as either permanent wetlands or water bodies by the GLCC.AVHRR database, GLCC.MODIS database, Global Lakes and Wetlands Database (GLWD) and West Siberian Lowland Peatland Database (WSLPD).

bases (Figure 4 and Table 4). The GLCC.MODIS database contains far fewer wetlands than the other three databases. Also, the GLCC.AVHRR database contains few wetlands in the southern half of the region, in stark contrast to the GLWD and WSLPD products. Furthermore, the GLWD clearly incorporates wetland data from GLCC.AVHRR, as evidenced by the east-west trending band of wetlands in both maps across the northern half of the region (Figure 4). The GLWD also reflects many of the same general patterns of wetland extent as the WSLPD, but with significantly lower spatial detail. To quantify these general observations, we separated category 11 (permanent wetlands) and category 17 (water bodies) from the remaining 15 IGBP categories in the GLCC.AVHRR, GLCC.MODIS and field databases, enabling the three products to be directly compared to the GLWD and WSLPD lake and wetland data products. We determine that the percentages of land surface area represented as permanent wetlands in the West Siberian region range between 2% (GLCC.MODIS), 8% (GLCC.AVHRR), 23% (GLWD), 24% (WSLPD) and 26% (field database) (Table 4). Agreement with field observations ranges between 2% (GLCC.MODIS), 23% (GLCC.AVHRR), 45% (GLWD), and 56% (WSLPD) (Table 4). It is clear that while all the databases examined underestimate wetlands and open water, those specifically developed for this purpose (GLWD and WSLPD) perform better than the more widely used, multiclass land cover products. In contrast to permanent wetlands, water bodies

Table 4. Percentage of Area Within the Total West Siberian Region That is Classified as Permanent Wetlands or Water Bodies[a]

	Permanent Wetlands		Water Bodies	
	Percentage of Total Land Area	Agreement With Field Observations	Percentage of Total Land Area	Agreement With Field Observations
GLCC.AVHRR	8%	23%	3%	5%
GLCC.MODIS	2%	2%	2%	0%
GLWD	23%	45%	2%	2%
WSLPD	24%	56%	3%	2%
Field	26%	N/A	3%	N/A

[a]Classifications are as mapped in Figure 4. In the case of the field database, this is the percentage of the land cover point observations that is classified as permanent wetlands or water bodies (i.e., 554 of 2161 or 64 of 2161 points, respectively). It is further denoted what percentage of these permanent wetland and water body field observations are in agreement with the four land cover databases.

cover far less of the West Siberian land surface area, ranging from only 2–3% of the total region (Figure 4 and Table 4). Furthermore, the agreement of our field observations with these water bodies in the four digital databases is substantially poorer (only 2–5%) than with permanent wetlands (Table 4) and in part may occur owing to the numerous small lakes located within the region.

3.3. Broad-Scale Evaluation of Latitudinal Trends

[16] Analysis of the broader-scale latitudinal distribution of land cover (GLCC.AVHRR, GLCC.MODIS and field databases) and water bodies/wetlands (all products) provides further insight into the differences and similarities between the five databases. Distinctive latitudinal patterns in land cover are apparent in all of them (Figures 5 and 6). For open water bodies, all databases show low occurrence across all latitudes except for our field data from ~65–66°N, where this class comprises ~12% of our observations (Figure 5). For wetlands, the ground data show low occurrence at both low and high latitudes, peaking at ~62°N. Similarly, the GLWD and GLCC.AVHRR databases classify the latitudinal distribution of wetlands with a high occurrence at midlatitudes and low occurrences at low and high latitudes in the region. However, both databases share identical peaks in wetland abundance from 64–65°N (Figure 5). This most likely reflects the fact that the GLWD incorporates data from the GLCC.AVHRR database, apparent as the identical band of east-west trending wetlands in the northern portion of the region for both databases (Figure 4). The field database and WSLPD also reflect a similar latitudinal distribution of wetlands throughout the region, with few wetlands at lower latitudes and a peak around 62°N–63°N (Figure 5). The peak occurring at 67°N–68°N may be an artifact of the few observation coordinates at these latitudes (i.e., N_f = 36). Although the latitudinal patterns are similar to the WSLPD, our field observations classify the land surface as wetlands more frequently than the WSLPD as well as all other databases in this study (Table 4).

[17] The latitudinal distribution of the 15 remaining IGBP classes is presented for the ground-truth, GLCC.AVHRR and GLCC.MODIS databases in Figure 6. Few or none of the field observations identify the presence of evergreen broadleaf forest, deciduous broadleaf forest, closed shrublands, savannas, cropland/natural vegetation mosaic, snow and ice, and barren or sparsely vegetated land cover. These categories are also seldom identified in either GLCC product. Instead, field observations indicate dominance of per-

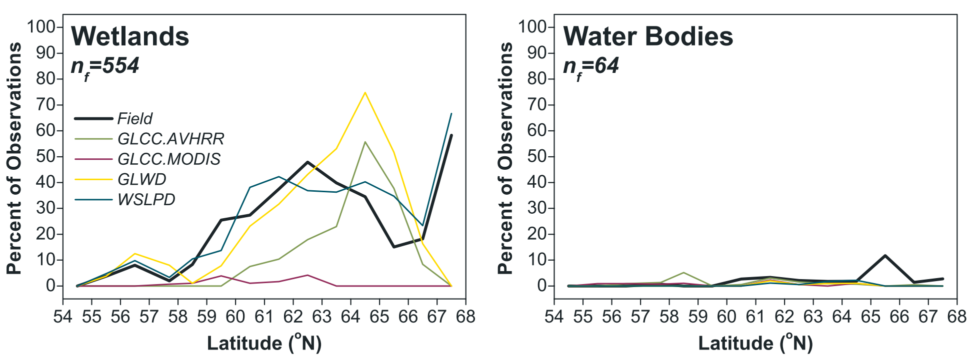

Figure 5. Percentages of the 2161 ground-truth sites (binned by latitude) identified as either permanent wetlands or water bodies in the field, GLCC.AVHRR, GLCC.MODIS, GLWD and WSLPD databases. Note that the binned values are determined from the same 2161 locations in all five data sets. The total number of field samples (n_f) classified for each category is shown on each plot. The number of sample sites (N_f) falling within each latitude bin are: N_f = 8 for 54–55; N_f = 106 for 55–56; N_f = 112 for 56–57; N_f = 149 for 57–58; N_f = 96 for 58–59, N_f = 51 for 59–60; N_f = 186 for 60–61; N_f = 357i for 61–61; N_f = 190 for 62–63; N_f = 113 for 63–64; N_f = 278 for 64–65; N_f = 265 for 65–66; N_f = 214 for 66–67; and N_f = 36 for 67–68.

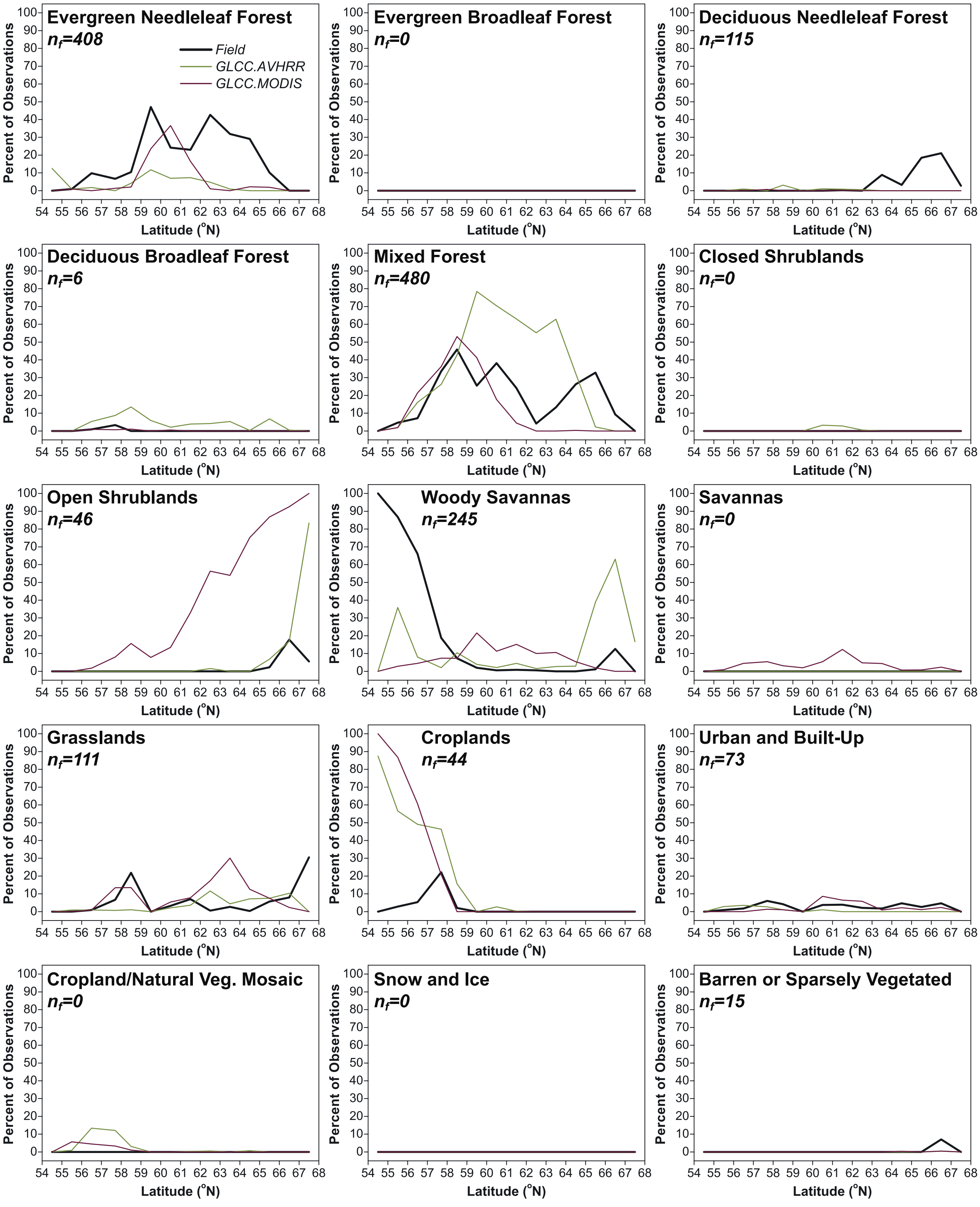

Figure 6. Percentages of the 2161 ground-truth sites (binned by latitude) identified as the remaining 15 IGBP land cover categories in the field, GLCC.AVHRR and GLCC.MODIS databases (see Figure 5 for permanent wetlands and water bodies in all five databases). The binned values are determined from the same 2161 locations in all three data sets. The total number of field samples (n_f) classified as each of the categories is denoted on each plot. The number of samples within each latitude bin (N_f) is the same as in Figure 5.

manent wetlands, water bodies, evergreen needleleaf forest and mixed forest at mid-latitudes (~58°N–64°N); deciduous needleleaf forest, mixed forest and open shrublands at high latitudes (~64°N–68°N); and woody savannas at low latitudes (~54°N–58°N). Some broad similarities are also seen in all three databases, in particular: (1) clear prevalence of evergreen needleleaf forest and mixed forest in the midlatitudes of the region where boreal forest predominates; (2) prevalence of open shrublands at high latitudes where tundra vegetation exists; (3) prevalence of woody savannas at the highest and lowest latitudes; (4) some presence of grasslands throughout all latitudes; and (5) occurrence of croplands at lower latitudes. However, there are also distinct disagreements between our ground-truth data and the GLCC.AVHRR and GLCC.MODIS products, most notably: (1) at midlatitudes (~58°N–64°N), the GLCC.AVHRR database underestimates evergreen needleleaf forest in favor of mixed forest; (2) at low latitudes (~54°N–58°N), both the GLCC.AVHRR and GLCC.MODIS databases underestimate woody savannas in favor of croplands; and (3) at high latitudes (~64°N–68°N), both the GLCC.AVHRR and GLCC.MODIS databases underestimate deciduous needleleaf forest in favor of woody savannas or open shrublands, respectively. From Tables 2 and 3, it appears that item 3 occurs because the GLCC.AVHRR and GLCC.MODIS databases tend to identify woody savannas or open shrublands, instead of the deciduous needleleaf forest observed in the field. Tables 2 and 3 also suggest that overall, the GLCC.AVHRR database agrees slightly better with the field database (22%) than does the GLCC.MODIS database (11%), although agreement with both products is low.

4. Discussion

[18] There is a critical need for accurate land cover maps in northern regions for resource assessment, biophysical modeling, carbon and trace gas studies, and to assess possible terrestrial responses and feedbacks to climate change. Results from this study reveal severe discrepancies in current representations of boreal forest and tundra vegetation, the boundaries between them, and their distributions across northern landscapes. This is of particular concern in West Siberia, where potential biophysical feedbacks play key roles in global climate change through land-atmosphere exchanges of energy, water, carbon and greenhouse gases [e.g., *Lashof et al.*, 1997; *Kittel et al.*, 2000; *Shaver et al.*, 2000; *Chapin et al.*, 2005]. For instance, northward expansion of boreal species would substantially decrease albedo, thereby increasing sensible heat flux to the atmosphere causing further warming [*Chapin et al.*, 1997; *Shaver et al.*, 2000; *Chapin et al.*, 2005]. It is also hypothesized that the tundra-taiga ecotone controls the summer position of the Arctic Front through its effects on energy partitioning and surface conditions [*MacDonald*, 2002, and references therein]. Therefore any movement in treeline may directly affect regional climatology and synoptic weather patterns controlled by the Arctic Front. It is likely that the current bioclimatic zones in West Siberia will migrate northward in response to expected warming in the region. A vegetation shift and intensification of vegetation productivity in tundra regions is in fact already apparent, with a significant increase in tundra shrub abundance [*Sturm et al.*, 2001] and observable pulses of tree invasion into tundra environments across Siberia [*Esper and Schweingruber*, 2004] over the past several decades. However, results of this study suggest that our knowledge of even current vegetation distributions is suspect. Even for the simplified 17-category IGPB scheme, the two most widely used global land cover products (GLCC.AVHRR and GLCC.MODIS) show low agreement with each other and with field observations. Although these two products utilize satellite data imaged nearly 10 years apart (1992–1993 for GLCC.AVHRR and 2000–2001 for GLCC.MODIS), the observed differences are too great to reflect true vegetation changes in the region. Even poorer corroboration is provided by the ground-truth data, with only 22% overall agreement with GLCC.AVHRR and 11% agreement with GLCC.MODIS. There is better, qualitative agreement among all databases in terms of coarse-scale (one degree) latitudinal distributions of land cover, but distinct differences remain as described in this study.

[19] In general, all four data products examined tend to underestimate the extent of permanent wetlands and water bodies, particularly the GLCC.AVHRR and GLCC.MODIS databases with only 23% and 2% agreement with ground-truth, respectively. The wetland-specific GLWD and WSLPD databases do display better agreement (48% and 56%, respectively) but still underestimate their prevalence (Table 4). Similar to vegetation cover, such large discrepancies among digital representations of surface water raise troubling questions about out current knowledge of current hydrological conditions, let alone our ability to predict future change. Lakes and wetlands are currently important sources of CH_4 and CO_2 to the atmosphere [*Kling et al.*, 1991; *Roulet et al.*, 1992; *Christensen et al.*, 1996; *Panikov*, 1999] and figure importantly in future climate scenarios given their large stocks of sequestered carbon [*Gorham*, 1991; *Sheng et al.*, 2004; *Smith et al.*, 2004]. In addition, while northern wetlands are currently a significant source of global atmospheric methane [*Roulet et al.*, 1992; *Christensen et al.*, 1996; *Panikov*, 1999], these emissions may change dramatically with surface wetness [e.g., *Laine et al.*, 1996; *Moore et al.*, 1998]. Furthermore, a transition from nonvascular plants (which have little control over water loss) to woody, vascular plants (which more effectively resist water loss) would result in both a decrease in latent heat flux and an increase in sensible heat flux, thus reducing evapotranspiration in addition to enhancing warming in the atmosphere [*McGuire et al.*, 2002]. This is particularly important in West Siberia, with its current predominance of nonvascular *Sphagnum* mosses throughout much of the region [*Kremenetski et al.*, 2003]. In fact, the hydrology of West Siberia may already be changing: A significant decline in the overall abundance and area of lakes has occurred over the past 25 years, perhaps from the thawing of permafrost [*Smith et al.*, 2005] owing to recent warming throughout the region [*Frey and Smith*, 2003]. However, we unfortunately may not be well equipped with sufficiently accurate maps of

the current distribution of lakes and wetlands to effectively monitor or model this change.

5. Concluding Remarks

[20] Digital representations of land cover and surface water are a core requirement for a wide range of mapping, change detection and biophysical modeling studies. Accurate knowledge of both is particularly critical for West Siberia and other northern wetland environments, where impacts of warming on vegetation and hydrology may trigger important feedbacks to regional and global climate. Unfortunately, none of the four data products evaluated in this study show strong agreement with our extensive new database of field observations, raising questions about their value in high-latitude, wetland-dominated regions. More research is needed to determine why all products universally underestimate wetlands and open water bodies; why GLCC.AVHRR tends to classify evergreen needleleaf forest as mixed forest; and why both the GLCC.AVHRR and GLCC.MODIS tend to classify woody savannas as croplands. Both GLCC products also have difficulty classifying deciduous needleleaf forest, in favor of woody savannas and open shrublands, respectively. Finally, we note that databases compiled from multiple legacy sources (e.g., the GLWD) propagate the inaccuracies of their predecessors, thereby compounding errors of differing magnitude within a single product. While this problem has recently been mitigated through development of a global hydrologic data set developed from Shuttle Radar Topography Mission data (http://edc.usgs.gov/products/elevation/swbd.html), these data exist only southward of 60°N. Therefore a strong opportunity exists for an analogous new, uniform wetland/water body product for northern latitudes. Until these deficiencies are addressed, we may be severely handicapped in our ability to model regional and global change in important northern environments like West Siberia.

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