Biogeosciences Discussions

Manuscript: High resolution wetland mapping in West Siberian taiga zone for methane emission inventory

Author's Reply to Referees #1 and #2:

Dear Editor,

This is our author reply to the two Anonymous Referees. We wish to thank both referees for their time and care in providing comments on our manuscript. We will answer each in turn beginning with Referee #1. Our comments are presented in dark blue font. Our changes in manuscript are presented in blue font. Each Anonymous Referee's original comments are in black. Many small revisions were also made in the manuscript (see marked-up version) but not mentioned here.

Response to the first referee

1. The contents of the paper and the text, particular the language, need substantially more work. Overall, more clarity is needed. The method section lacks detail. Some of the background information provided belongs either into the discussion section or, if not relevant for the development of the product, should be removed. Some of the remote sensing terms in use need more clarification.

Thank you very much for this detailed, useful and reasonable review! We tried to take into account all your comments and rewordings to make our manuscript clearer for readers. To make research more substantial, we will add supplements with spatial distributions of wetland ecosystem areas of 0.1°×0.1° at the final stage of revision (Fig. 4 from the paper).

2. Please run the document through an English grammar/syntax check (e.g. Word) or invite an English speaker to improve manuscript language, reading flow and understanding.

We have checked our English using NPG Language Editing service. Nevertheless, as there are still problems with the language, we will use Copernicus English language copy-editing service in case of publication. In addition, we would like to express our sincere gratitude for so many rewordings, which were very helpful!

3. Title: I suggest a new title: “High-resolution satellite mapping of West Siberian Lowland wetland complexes: Implications for methane emissions”

We agree that current title is not accurate enough. We found it reasonable to change it to:

- «Mapping of West Siberian taiga wetland complexes using Landsat imagery: Implications for methane emissions».

We decided to mention «Landsat» because it answers the question of map resolution. Previously used «High-resolution satellite mapping…» was not distinct. We decided to mention «taiga» instead of West Siberian Lowland (WSL) because taiga zone was actually mapped and it is two times smaller than WSL.

4. “sink carbon and emit methane”. Inconsistent since methane also contains carbon. Do you mean sink CO2 and emit CH4?

- Revised: «sink carbon dioxide and emit methane»

5. L.3-5 Reworded: Fine-scale heterogeneity of wetland landscapes poses a serious challenge when generating regional-scale estimates of greenhouse gas fluxes from point observations.

   L. 7-8: Reworded: “Training data consists of high-resolution images and extensive ïn˘A¸eld data recorded in 28 test areas.”

   L.7-10. Reworded: “The classification scheme developed aims at supporting methane inventory applications and includes 7 wetland ecosystem types comprising 9 wetland complexes.”

   L. 24-26. Reworded: “The West Siberia Lowland (WSL) is the world’s largest high-latitude wetland system and experiences an accelerated rate of climate change (Solomon et al., 2007).”

   P. 20151 L. 1-3 Reworded: “Poorly constrained estimates of wetland and lake area constitutes a major uncertainty in accurately predicting current and future greenhouse gas emissions (Melton et al., 2013; Turetsky et al., 2014; Petrescu et al., 2010).”

   L. 4-7 Reworded: “Fine-scale heterogeneity of WSL’s wetland landscapes (Bohn et al., 2007; Eppinga et al., 2010; Bridgham et al., 2013) is not accurately accounted for when wetland CH4 emission inventories (Glagolev et al., 2011) and net primary production (Peregon et al., 2008) are generated from point-scale field observations.”

Revised. Thank you!

6. L. 8-9: Corrected: : : : fails to capture fine-scale : : :

- Corrected to: «fail to capture fine-scale…»

7. L. 14: “surface” What surface? The soil surface? The leaf surface? The land surface? Does wetland area equate inundation area? Please qualify your statement.

Vegetation cover in wetlands is usually dominated by mosses (sphagnum, green or brown mosses). In these wetlands, the border between soil (dead mosses) and vegetation (live mosses) is vague. Therefore, abovementioned «surface» is actually moss (usually sphagnum) surface. When water is more than 3-5 cm below the moss cover, wetlands look as not saturated with water (Fig. 1a from the response). Inundation area (Fig. 1b) corresponds only to the situation when water is under the moss cover or soil cover when mosses are absent. Water table is 10 cm below the sphagnum surface at Fig. 1a and is 5 cm under the sphagnum surface at Fig. 2b.

Fig. 1. «Unsaturated» wetland area (a; oligotrophic hollow) and inundation area (b; waterlogged hollow)

- Revised version: «Some products (Schroeder et al., 2010; Papa et al., 2010) tend to map only inundation, overlooking areas of «unsaturated» wetlands where the water table is below the moss cover. Because boreal peatlands does not experience prolonged inundation, such products underestimate their area (Krankina et al., 2008). Uncertainty in wetland inventory results in severe biases in CH4 emission estimates, the scale of differences has been shown by Bohn et al. (2015).»

8. L. 16 “Modelers ...” Can you be more specific? 20152 L. 9 “and the model assessment.” Unclear. Please qualify!

We meant all modelers, simulating natural ecological processes. For example, modelers studying GHG emissions (CO_2, CH_4, N_20, CO), carbon balance, NEE (net ecosystem exchange), biomass, NPP (net primary production), peat storage, spatiotemporal dynamics of wetlands (Zimmermann and Kaplan, 2016), regional hydrology (Baird et al., 2012; Bohn et al., 2007). «The model assessment» means the model adequacy assessment or how well do the model agree with experimental data.

However, the study mainly aimed at CH_4 emission models. Thus, we added more details to the text (see below). In addition, we cite the study by Bohn et al. (2015), which presents results of

21 models and 5 inversions assessment over WSL in terms of CH_4 emission. In this study, authors also highlight that wetland area bias is the primary driver of CH_4 emission model spatial uncertainties.

- Added text: «Uncertainty in wetland inventory results in severe biases in CH4 emission estimates, the scale of differences has been shown by Bohn et al. (2015).»
- Revised: «Modelers simulating methane emission are in need for high-resolution wetland maps that do not only delineate wetlands but also identify the major sub-types to which different environmental parameters could potentially be applied (Bohn et al., 2015).»
- Revised: «The objectives were: first, to develop a consistent land cover of wetland classes and its structural components; second, to provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, net ecosystem exchange, biomass, etc) and validation of the process models.»

9. Same line: "high-resolution map" Map of what?

- Revised: «high-resolution wetland map»

10. L. 20 "in aggregate to limited or no ground truth data" Please rephrase this, if possible!

- Revised: «Several wetland maps have been used to define the wetland extent in WSL, however their application to net primary production (NPP) and methane emission inventories was accompanied by difficulties due to crude classification scheme, limited ground truth data and low spatial resolution.»

11. L. 26 "high-resolution images" Images of what? Please specify!

We apologize for mistake; they actually used aerial photographs:

- Revised version: «Peregon et al. (2005) digitized and complemented this map by estimating the fractional coverage of wetland structural components using Landsat images and aerial photographs for five test sites.»

12. L. 27 "upscaled estimations" What estimations?

- Revised: «However, the limited amount of fractional coverage data and coarse resolution still result in large uncertainties in upscaling methane fluxes (Kleptsova et al., 2012).»

13. L. 12 "Urals" Do the authors mean the Ural Mountains? L. 13 "stretching" Remove. L. 14 "great expanse" can be reworded to "vast expanse"

Revised.

14. L. 14. “flat topography” Nothing has a flat topography. Topography is the study of landforms etc.. If authors talk about the relief of the region then “flat terrain” is appropriate. This will describe that the relief of the region is rather flat than being mountainous/hilly. Please correct all subsequent instances.

Corrected to «flat terrain».

- Revised: «Because of its vast expanse and flat terrain, the vegetation cover ... It is characterized by flat terrain with elevations of ... The excess water supply and flat terrain with poor drainage provides favorable conditions for wetland formation.»

15. L. 21 “: : : impeded” Do authors mean “poor”?

Revised.

16. P. 20153 L. 1-6 Please shorten this or drop all together. If authors use any of this information later i.e. in their discussion, then place it there. Now that I finished this section, I believe that authors should shorten the whole section. Focus on mentioning only the important stuff or cite the relevant literature for reader to look up, then move on.

Initially, it was Editor's comment to «…briefly summarize the major findings of Kremenetski et al. (2003) on P4 L2». To shorten the whole section, we removed this text:

«Large fraction of the area, including watersheds and floodplains, is waterlogged. The hydrographic structure of this zone differs from the northern and southern parts of the WS. The largest peatlands are most typical of the central flat parts of the watersheds where, together with forests, they comprise the zonal vegetation and cover vast territories (Solomeshch, 2005). Comprehensive synthesis of Russian literature regarding the current state of the WS peatlands, their development and sensitivity to climatic changes was made by Kremenetski et al. (2003). The study summarizes information about WS geology, hydrology, climate, vegetation, and peatland zonation. Basing on existing Russian data, authors found that the mean depth of peat accumulation in the WSL is 256 cm and the total amount of carbon stored there may exceed 54×109 metric tons.»

17. P. 20154 L. 5 Which Landsat did the majority of images come from? Landsat 4, 5?

- Corrected to: «Majority of the images were Landsat 5 TM scenes from July 2007.»

18. L. 11-12. Why did the authors do this transformation? Was the native projection of images not good enough? Did it vary?

The initial Universal Transverse Mercator (UTM) projection divides WSL into 5 zones, which is inconvenient. Albers Equal Area projection represent WSL as the whole region (without dividing into zones) and is appropriate for area calculations.

19. L. 16. 5th Landsat band. Can you provide wavelength or wavelength range for this band?

- Revised: «the 5th Landsat channel (1.55-1.75 µm)».

20. L. 17. What do authors understand as inundation? Can channel 5 be used to mask out standing water that is covered by vegetation? The latter areas are considered inundated but can authors can sense them with Landsat? I believe authors can mask out all open water including inundation that is not masked by vegetation. Please be more specific, else define your terms.

We define "inundation" as standing water above the soil surface (Fig. 1b from the response). When sphagnum mosses are present, we define "inundation" as standing water above the moss surface, because the border between live plants and peat is very vague. Channel 5 can be used to mask out standing water that is covered by grass or shrub vegetation with low projective cover, when water or water-saturated soil can be seen through it. In general, grass or shrub vegetation of taiga wetlands become sparser with increasing inundation. Therefore, we usually can mask out such environments. In case of sphagnum mosses, areas with water under or 3-5 cm below moss surface can be sensed using 5th Landsat band. Such areas were mentioned in the paper as «the most inundated». However, in case of dense tree layer (e.g. wooded swamps), we actually cannot sense them using only 5th channel.

- To be more specific, we changed the sentence: «Thresholds of the 5th Landsat channel (1.55-1.75 µm) was used to mask water bodies and many inundated areas (even vegetated) with the water level up to a few cm below the soil surface.»

21. L. 29 Is high-resolution imagery from Google Earth multispectral? Can the author say something about the characteristics of these images? Spatial and spectral resolution, sensor, acquisition dates etc. P. 20157 L. 10 Which high-resolution images? Google Earth? If so, are they multispectral?

- Revised: «As a result, we had to rely mostly on high-resolution images available from Google Earth. They came from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics; multispectral images were reduced to visible bands (blue, green, red) and had spatial resolution of 1-3 meters.»

Unfortunately, there were usually no meta-data available regarding image acquisition dates and spectral transformations of Google Earth products.

22. P. 20155 L. 3 Who or what are “they”?

- Changed to «The dataset was…».

23. L. 6 “contiguous”. Do you mean “adjacent”? L. 7 Please define auxiliary data coverage? Do authors mean ancillary data? Remember: readers want to know what they are and what was done with them. Provide more detail, please.

It was removed to make the paragraph clearer.

- Revised: «The processing started with mapping scenes where ground truth data and high-resolution images are extensively available, so the classification results could be checked for quality assurance; mapping continued through adjacent images and ended at the less explored scenes with poor ground truth data coverage.»

24. L. 7-11 How did the authors judge the quality of their training samples? Did they quantify spectral separability prior to classification?

Training data histograms were checked for normality to judge the quality of training samples. The Bhattacharyya distance measure was calculated to check the relative separability between pairs of classes. Then the only training fields were classified and resubstitution errors were calculated (difference between the response training data and the predictions based on the input training data)(Jain et al., 2000). If inspection of these results indicated good accuracy (more than 80% overall) with no fields showing unreasonable or unexplainable errors, spectral separability was suggested to be satisfactory, so the classification of the test areas and then of the whole area was started.

- Revised: «…(ii) all of the samples must be at least 10 pixels in size with an average sample area of approximately 100-200 pixels. The Bhattacharyya distance was used as a class separability measure. The classifier was designed using training samples and then evaluated by classifying input data. The percentage of misclassified samples was taken as an optimistic predication of classification performance (Jain et al., 2000). When accuracy of more than 80% across the training set was attained with no fields showing unreasonable or unexplainable errors, the classification process was started. Classification mismatch between scenes was minimized by placing training samples in overlapping areas.»

25. L. 16 Patch effects. This looks as if it is a result so likely it does not belong here.

It was removed.

26. L. 19 What are the filter parameters? Any weights? What is the size?

- Revised: «Noise filter was applied to eliminate objects smaller than 2×2 pixels. After that, a 10×10-pixel moving window was used to determine the dominant class, which was further assigned to the central 4×4-pixel area.»

27. P. 20156 L. 5 I suggest to replace “water” with “open water “. L. 6 Same thing. Suggest authors say ”Open water bodies fewer : : :”. L. 21 “resolution cell size” Do authors mean “sensor spatial resolution”?

Revised.

28. L. 8-12 I suggest that authors provide more detail on the unsupervised classification unless this is the “Peregon approach”.

- We apologize for vagueness. Revised: «To merge typologies, we estimated relative areas of wetland ecosystems within each wetland complex of the final map. Depending on heterogeneity, 8 to 27 test sites of 0.1-1 km2 size were selected for each heterogeneous wetland complex. High-resolution images of 1-3 m resolution corresponding to these areas were classified in Multispec v.3.3 using visible channels. An unsupervised ISODATA classification was done on the images specifying 20 classes with a convergence of 95%. Obtained classes were manually reduced to seven wetland ecosystem types. Their relative proportions were calculated and then averaged among the test sites.»

29. L. 26 How did authors manage this? Were floodplains masked prior to this? If so, what data was used for masking floodplains?

Floodplains were classified simultaneously with wetlands using Landsat images. The latter were mainly chosen for the peak of growing season, when floodplains are not inundated. «Dry» floodplains and wetlands are easily separated from each other because of differences in spectral signatures, especially in 5th band values.

- Revised: «Third, in this study, we only consider peatlands and water bodies; floodplain areas were separated from wetlands during the classification process.»

30. P. 20158 L. 5-6 Context?

- We moved the sentence further. Revised: «Based on Landsat imagery, we developed a high-resolution wetland inventory of the WSL taiga zone (Fig. 2). The total area of wetlands and water bodies was estimated to be 52.4 Mha. West Siberian taiga wetlands are noticeable even from global prospective. The global total of inundated areas and peatlands was estimated to cover from 430 (Cogley, 1994) to 1170 Mha (Lehner and

Döll, 2004) as summarized by Melton et al. (2013); therefore, taiga wetlands in WSL account for approximately from 4 to 12% of the global wetland area.»

31. L. 25 “feasible” I believe that “reasonable”, “practical” or “economical” may be better words here. Feasible simply means it’s possible.

Revised.

32. P. 20159 L. 26-27 Please define patch effect. And where do I find it? “ensue from” Do you mean “result from”? Abrupt leaps? What is this and where do I find it? Is this shown in any of the figures?

We decide to remove this part as unimportant. Initially, patch effect can be observed at Fig. 4 from the paper like barely visible vertical distortion. It results from spectral inconsistency between adjacent images, not completely smoothed by designating training sites at overlapping areas.

33. P. 20160 L. 4 reworded “low evaporation and minimal runoff” L. 7 reworded “for one hundred kilometers” L. 16 “cupola” I suggest to use “dome” here. L. 27-P.20161 L. 1 Suggest rewording: e.g. “The southern and middle taiga wetlands exhibit similar spatial patterns; however, the area of fens increases in a stepwise fashion due to the abundance of carbonate soils and higher nutrient availability.” L. 1-5 Suggest rewording: e.g.“Velichko et al. (2011) provide evidence for the existence of a vast cold desert in the northern half of the WSL, whereas the southernmost part was an area of loess accumulation. The border between fen and bog-dominated areas extends near 59â°U ̧eN, and corresponds to the border between the southern and middle taiga zones (Fig. 4c and e).” L. 26 “disposed” Do authors mean “arranged”?

Revised.

34. L. 15 “neighboring classes” Spatially or spectrally close?

Close by environmental parameters (water table level, vegetation, trophicity level) and, as a result, spectrally close. There are many examples in the papers (see below), so we moved this sentence further to the beginning of the corresponding paragraph.

- Revised: «Misclassifications usually occurred between similar classes introducing only a minor distortion in map applications. Patterned fens and open bogs were classified with the lowest producer’s accuracy (PA) of 62%. Patterned fens include substantial treeless areas, so they were often misclassified as open fens. They were also confused with RHCs due to the similar “ridge-hollow” structure. Some open bogs have tussock shrub cover with sparsely distributed pine trees provoking misclassification as RHCs and pine bogs. Open fens have higher user's accuracy (UA) and PA…»

35. L. 22-26 Confusing. Suggest rewording or explain in more detail.

- Revised: «Wetland complexes within large wetland systems had the highest classification accuracies. In contrast, the uncertainties are particularly high for small objects. It is of special importance in southern part of the domain, where highly heterogeneous agricultural landscapes neighbour upon numerous individual wetlands of 100-1000 ha area. Several vegetation indices was tested to map them; however, the best thresholding result was achieved by using Landsat thermal band…»

36. P. 20162 L. 9-10 How so? Can low-resolution images do a better job? Explain.

Due to economic reasons, we used high-resolution images with bands of only visible light, while near and shortwave infrared channels are the most useful for distinguishing wetlands with different trophic state as a result of their ability to highlight vegetation cover features. Therefore, in some case, Landsat images actually do better job.

- Revised: «Open fens have higher user's accuracy (UA) and PA; however, visible channels of high-resolution images poorly reflect trophic state, which underrates classification errors between open bogs and open fens.»

37. L. 14-16 Suggest rewording: "During dry period, swamps were often confused with forests, whereas in the field they can be easily identified through the presence of peat layers and a characteristic microrelief. " L. 20 "snow melt" ? L. 24 "indicate"? Do authors mean "achieve"? P. 20163 L. 12 "turn" Do authors mean "develop"? L. 14 "commonly" Do authors mean "typically"? L. 15 "Oppositely" Do authors mean "in contrast"? L. 18-21 Suggest rewording.

Revised.

38. L. 17 "interannual variability" of what?

- Revised: «Interannual variability of water table level in WSL wetlands (Schroeder et al., 2010; Watts et al., 2014) also makes impact on mapping results.

Удалено: Interannual variability of water table level also occurs in WSL (Schroeder et al., 2010; Watts et al., 2014).»

39. L. 18 "reasonable" Do authors mean "important"?

We removed this sentence.

40. P. 20164 L. 1 "results from PALSAR." Please cite Clewley et al (2015) and Chapman et al. (2015)

- Revised: «New methodologies and protocols are needed to improve our ability to monitor water levels (Kim et al., 2009). Observations of soil moisture and wetland dynamic using radar data such as PALSAR (Chapman et al., 2015; Clewley et al., 2015) and Global Navigation Satellite Signals Reflectometry are promising (Chew et al., 2016; Zuffada et al., 2015). Advanced classification techniques such as fuzzy logic can be applied for mapping fine-scale heterogeneity (Adam et al., 2009). Recent innovations in wetland mapping were described by Tiner et al. (2015).»

41. L. 7 Schroeder et al. (2010, 2015) actually combined active with passive microwave sensors to measure open water.

- Revised: «Although the synergistic combination of active and passive microwave sensor data is advantageous for accurately characterizing open water (Schroeder et al., 2010) and…»

42. L. 27 “describe” Sure. But authors should also mention that they “developed” their map.

- Revised: «In this study, we developed a map representing the state of the taiga wetlands in WSL during the peak of the growing season.»

43. P. 20165 L. 10-13 Suggest rewriting.

- Revised: «The resulting quantitative definitions of wetland complexes combined with a new wetland map can be used for the estimation and spatial extrapolation of many ecosystem functions from site-level observations to the regional scale. In the case study of WS’s middle taiga, we found that applying the new wetland map led to a 130% increase in the CH_4 flux estimation from the domain (Kleptsova et al., 2012) comparing with estimation based on previously used SHI map. Thus, a considerable reevaluation of the total CH_4 emissions from the entire region is expected.»

44. L. 17 “most ambiguous” Do authors mean “least discernable”? L. 20 “embracing at least”? “As in “covering at least”? L. 23 “was oriented” Do authors mean “geared towards improving methane emissions : : :”?

Revised. Thank you!

Response to the second referee

1. In your case you used moderate resolution data such as LANDSAT 7 with pixel size of which in my opinion is not suitable to quantify peatland microforms and its fine scale heterogeneity such as hummocks, hollows and mud bottom hollows and many small pools less than the size of your LANDSAT data resolution that has significant contributions to the overall methane emissions from the peatlands/wetlands. Further, a spectral classification technique such as the one you have applied using maximum likelihood classifier on the imagery with 30 m pixel resolution would result in miss classifications, and is not suitable for classifying peatland microforms such as mentioned above… Your current work does not make a significant improvement in accurately quantifying GHG budget.

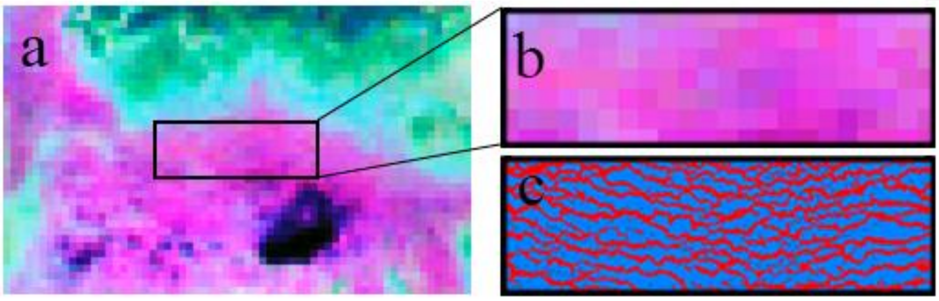
It was not clear from the abstract and introduction that actual application of the remote sensing data to wetland CH_4 emission inventory as done by Glagolev et al (2011) involves combining multiple scales of the geographical information. Previous analysis made by Peregon et al (2008, 2009) relied on combining 3 scales: a) whole-region map of 22 wetland complexes at 1:2.5M scale, b) wetland type area fractions for wetland types distinguishable on 30 m resolution image derived from one representative Landsat image for each of 5 latitudinal zones, and c) microlandscape area fractions, such as fractional areas of lake, hollow, ridges within patterned wetlands, estimated via mapping of several high resolution images available from Google Earth and other sources. Present manuscript reports an advance from the above mentioned 3-scale approach by implementing a whole-area coverage with Landsat-based mapping (Fig. 2 from the paper), removing uncertainty caused by relying on coarse resolution 1:2.5M scale map (SHI map; see comparison at Fig. 3 from the paper). In the case of applying this newly developed map for wetland emission inventory, a microlandscape area fraction tables by Peregon et al, (2009) or from other sources have to be used. In this study, microlandscape area fractions (or wetland ecosystem areas) were calculated using high-resolution (1-3 m) images of 8-27 test sites of 0.1-1 km^2 size for each wetland complex of the final Landsat-based map (Fig. 1c from the response). Wetland ecosystem areas scaled to 0.1×0.1 grid are presented in Fig. 4 from the paper – these areas can be directly used for methane flux calculations.

In other words, our wetland area inventory has two scales. First scale is the wetland map made by Landsat images of 30 m cell size with the minimum mapping unit of 2×2 pixels or 60×60 m^2. The classification scheme include 9 "wetland complexes", which are distinguishable by Landsat images and abundant in the WSL (Fig. 2 from the paper or Fig. 2a,b from the response).

We totally agree with you, that this scale is not suitable for methane inventory because of fine-scale heterogeneity.

However, within each wetland complex we can detect relatively homogeneous structural elements or “wetland ecosystems” with similar water table levels, geochemical conditions, vegetation covers and, thus, rates of CH_4 emissions (Sabrekov et al., 2013). We assigned 7 wetland ecosystem types (Table 1): open water, waterlogged hollows, oligotrophic hollows, fens, ryams, ridges, palsa hillocks. To calculate regional methane emission, areas of wetland ecosystems are required. We estimated these areas within each wetland complex of the final map using high-resolution images (1-3 m for multispectral images). This is a second scale of our wetland inventory. This scale was used for estimating methane emission (Fig. 4 from the paper; Fig. 2c from the response).

Fig. 2. Wetland ecosystem mapping using high-resolution images: a) Landsat image (4-5-3 bands) with 30 m resolution, b) ridge-hollow complex (RHC) at Landsat image, c) wetland ecosystems in RHC mapped by 1-3 m resolution images for the same territory (red – ridges, 37% of the area; blue – oligotrophic hollows, 63% of the area)



As methane flux data, we used extensive dataset from 28 test sites containing more than 1500 emission measurements. To catch all spatial variability of fluxes, we made many measurements and then obtained probability density distributions for each wetland ecosystem type in every climate zone. Our methane emission dataset is the single one based on large-scale and long-term field investigations. To be most useful, it should be combined with the appropriate map. Our previous estimate (Glagolev et al., 2011) was based on SHI map (Peregon et al., 2009). In this study, we tried to prove that the new map is more accurate: its resolution is higher, and the classification scheme was developed specially for our goals (Fig. 3 from the paper). We achieved a reasonable accuracy of 79%, while accuracy assessment of SHI map was not done at all.

As it was expected, wetland ecosystem areas have significantly changed in comparison to SHI map; in particular, we obtained larger spatial extent of high-emitting wetland types, which have an impact on CH_4 emission estimation. As it was cited in the paper, in the case study of WS's middle taiga, we found that applying the new wetland map led to a 130% increase in the CH_4 flux estimation from the domain (Kleptsova et al., 2012) in comparison with the estimation based on SHI map. Thus, we expect a considerable revaluation of the total CH_4 emissions from the whole region.

Actually, this revaluation is already made and it is considerable. New methane emission estimate is very close to 5 inversion estimates (Bohn et al., 2015). However, we decided (according to previous reviewer's advice) to divide the research into 2 parts: the current paper concerning the wetland map and the second paper concerning methane inventory. Therefore, the exhaustive answer about methane emission cannot be given within the bounds of this paper.

To sum up, we think that it is reasonable to state that: 1) our multiscale classification scheme is suitable for methane inventory; 2) new wetland map has better spatial resolution in comparison to previously used SHI map; 3) wetland ecosystem areas have significantly changed in comparison to previously used SHI map; 4) new map has potential to make a significant improvement in accurately quantifying GHG budget. To make research more substantial, we will add supplements with spatial distributions of wetland ecosystem areas of 0.1°×0.1° at the final stage of revision.

However, we understand that the paper needs to be clearer for the reader, so we would like to thank you again for useful comments! To bring more clarity, we have revised many paragraphs (see the paper). Besides that:

- We added new table with wetland ecosystem descriptions and water table levels (Table 1):

Table 1. Wetland ecosystem types

Wetland ecosystem	Short description	WTL, cm (1st/2nd/3rd quartiles)[1]
Open water	All water bodies greater than 2×2 Landsat pixels	-
Waterlogged hollows	Open water bodies fewer than 2×2 Landsat pixels or depressed parts of wetland complexes with WTLs above the average moss/vegetation surface	-10 / -7 / -4
Oligotrophic hollows	Depressed parts of bogs with WTLs beneath the average moss/vegetation cover	3 / 5 / 10
Ridges	Long and narrow elevated parts of wetland complexes with dwarf shrubs-sphagnum vegetation cover	20 / 32 / 45

Ryams	Extensive pine-dwarf shrubs-sphagnum peatland areas	23 / 38 / 45
Fens	Integrated class for various types of rich fens, poor fens and wooded swamps	7 / 10 / 20
Palsa hillocks	Elevated parts of palsa complexes with permafrost below the surface	Less than 45

[1] Positive WTL means that water is below average moss/soil surface; the data was taken from field dataset (Glagolev et al., 2011)

- We have rewritten «Wetland typology development» section: «As a starting point for the mapping procedure, a proper classification scheme is required. Congalton et al. (2014) showed that the classification scheme alone may result in largest error contribution and thus deserves highest implementation priority. Its development should rely on the study purposes and the class separability of the input variables. In our case, wetland mapping was initially conceived as a technique to improve the estimate of the regional CH4 emissions and, secondarily, as a base to upscale other ecological functions. WSL wetlands are highly heterogeneous, however, within each wetland complex we can detect relatively homogeneous structural elements or "wetland ecosystems" with similar water table levels (WTL), geochemical conditions, vegetation covers and, thus, rates of CH4 emissions (Sabrekov et al., 2013). To ensure a reliable upscaling, we assigned 7 wetland ecosystems in our classification scheme (Fig. 1; Table 1).

  However, wetland ecosystems generally have sizes from a few to hundreds of meters and cannot be directly distinguished using Landsat imagery with 30-meter resolutions. Therefore, we developed a second wetland typology that involves 9 mixed "wetland complexes" composing wetland ecosystems in different proportions (Fig. 1; Table 2). The classification were adapted from numerous national studies (Katz and Neishtadt, 1963; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompassed wooded, patterned, open wetlands and water bodies. The criteria for assigning wetland complexes were: (i) separability on Landsat images, and (ii) abundance in the WSL taiga zone. Each wetland complex represents integral class containing several subtypes differing in vegetation composition and structure. Subtypes were mapped using Landsat images and then generalized into final 9 wetland complexes basing upon ecosystem similarity and spectral separability.

  To merge typologies, we estimated relative areas of wetland ecosystems within each wetland complex of the final map. Depending on heterogeneity, 8 to 27 test sites of 0.1-

1 km2 size were selected for each heterogeneous wetland complex. High-resolution images of 1-3 m resolution corresponding to these areas were classified in Multispec v.3.3 using visible channels. An unsupervised ISODATA classification was done on the images specifying 20 classes with a convergence of 95%. Obtained classes were manually reduced to seven wetland ecosystem types. Their relative proportions were calculated and then averaged among the test sites.

Thus, we used multiscale approach relying in two typologies. First, typology of wetland complexes was used for mapping Landsat images; second, typology of wetland ecosystems was used for upscaling CH4 fluxes. The approach is similar to one devised by Peregon et al. (2005), where relative area proportions of "micro-landscape" elements within SHI wetland map were used for NPP data upscaling.

During wetland typology development, we made several assumptions. Firstly, the wetland complexes were considered as individual objects, while they actually occupy a continuum with no clustering into discrete units. Secondly, we assumed that all of the wetland water bodies originated during wetland development have sizes less than 2×2 Landsat pixels. They are represented by wetland pools and waterlogged hollows, which are structural components of RHLC. The rest of the water bodies were placed into the "Lakes and rivers" class. Third, in this study, we only consider peatlands and water bodies; floodplain areas were separated from wetlands during the classification process.

The concept of wetland ecosystems has merits for CH4 emission inventory. Methane emission depends mainly on water table level, temperature, and trophic state (Dise et al., 1993; Dunfield et al., 1993; Conrad, 1996). We take into consideration temperature, when we upscale fluxes separately for southern, middle and northern taiga. We take into consideration trophic state, when we map wetland complexes using multispectral Landsat images. We take into consideration water table level, when we map vegetation of wetland ecosystems with high-resolution images, because vegetation reflects soil moisture conditions. We do not directly consider smallest spatial elements as hummocks and tussocks. This omission introduces some uncertainty in regional CH4 emission estimate, which was evaluated by (Sabrekov et al., 2014). Accordingly, reliable estimate of CH4 fluxes accounting for fine spatial detail requires large number of measurements. Such heterogeneity is being addressed by measuring fluxes in all microforms in the field and then obtaining probability density distributions.»

- We have already changed title to «Mapping of West Siberian taiga wetland complexes using Landsat imagery: Implications for methane emissions».
- We have added information about ecosystem area change in comparison to SHI map: «Distribution of wetland ecosystem areas have changed significantly in comparison to SHI map (Peregon et al., 2009); in particular, we obtained 105% increase in spatial extent of CH_4 high-emitting ecosystems such as waterlogged, oligotrophic hollows and fens.»

2 You have reported burnt areas in the landscape but you did not explain how you distinguished mud bottom hollows and burnt areas which I suspect would have similar spectral signatures thus resulting in further misclassifications.

According to (Karofeld, 2004), we consider «mud-bottom hollows» as depressions on the bog surface where Sphagnum mosses have died. Such environments are rare in West Siberia; we have almost never found them for 8 years of regular field studies. They occupy small areas and are not important at the regional scale. Concerning burnt areas, their spectral signatures differ from wetland environments: values of 5th and 7th Landsat 5 TM bands in burnt areas are usually higher, e.g. (Pereira et al., 1999); Fig. 7.3 in their paper).

3 Suggestions: I suggest you get IKONOS data (both PAN and Multispectral data) and redo the classification using object based fuzzy logic techniques wherein you can define rules for all possible classes and expect an improved result. There are many good papers in the literature on the object based peatland classifications.

Thank you for suggestion! Fuzzy logic techniques are really interesting and promising. We are going to implement them for a few test sites in tundra zone in our future studies. Concerning area of whole WSL, first, we cannot afford data of such coverage. Second, the method is very time-consuming and expensive, but the improvement of results is not guaranteed. Thus, we are not sure, that advantages of fuzzy logic in our case will exceed disadvantages.

In this study, we present the map, which has already developed. Combining with multiscale approach, it can be used for methane emission estimation. We hope that it would be useful for scientific community right now, while we will aimed at applying advanced methods for mapping the rest of the domain.

- We added this text at the «Challenges and future prospects» section: «Advanced classification techniques such as fuzzy logic can be applied for mapping fine-scale heterogeneity (Adam et al., 2009). Recent innovations in wetland mapping were described by Tiner et al. (2015).»

Specific Comments:

4 When you say fine scale could you describe the resolution you are talking about?

Our wetland area inventory has two scales. First scale is the wetland map made by Landsat images of 30 m cell size. However, it is suggested that the smallest observable feature that can be identified need to be at least four contiguous pixels in size, so the minimum mapping unit is 2×2 pixels or 60×60 m^2. Second level is based on unsupervised classification of approximately 70 high-resolution images of 0.1-1 km^2 size. Resolution of multispectral imagery is from 1 to 3 meters depending on sattelite sensor.

«Fine scale» means a scale of wetland ecosystems, which is used in methane emission inventory. In size, it is from few meters in one dimension (in case of ridges) to several hundred meters in case of lakes and homogeneous wetland complexes. We have added these values, where it is possible, to make it clearer:

- …multispectral images were reduced to visible bands (blue, green, red) and had spatial resolution of 1-3 meters
- High-resolution images of 1-3 m resolution corresponding to these areas were classified in Multispec v.3.3 using their visible channels

5 P20152, L-20: Could you cite latest weather data, were you not able to get this information after the 1963 reference?

We are sorry for that, now information according to official National Atlas of Russia is presented. Data for this Atlas were obtained for 1970-2004.

- Revised: «Average annual precipitation is about 450-620 mm and evaporation is 360-500 mm, both increasing in north-south direction (National Atlas of Russia, 2008).»

6 What convention did you use for the classification of the peatland micro and macro structural elements? This is a pity that until date there is not a single acceptable convention on peatland classes that are globally acceptable within the community.

We totally agree that it is a pity. The situation is slightly at the national scale: many Russian studies have been carried out in the middle of 20th century under the aegis of government and USSR Academy of science (Katz and Neishtadt, 1963; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Masing et al., 2010). They resulted in developing the more or less conventional (for Russia) classification of wetland macrostructural elements. Many studies were performed in West Siberia, making it one of the best-studied region concerning wetland typology, hydrogeology, structure, vegetation cover, etc. In current research, I adapted this convention («wetland complexes» typology). As far as we know, it was published in detail only in Russian (e.g. Usova, 2009).

In the case of microstructural elements, the classification of «microlandscape» types made by (Peregon et al., 2005) was found to be the most appropriate. It was developed for WSL and aimed at upscaling NPP point observations. In current study, we adopted this classification to upscale CH_4 emission point measurements. It was called wetland ecosystem typology and include 7 ecosystem types (open water, waterlogged, oligotrophic hollows, fens, ryams, ridges, palsa hillocks). Surely, in the beginning of the study, we tried to find and apply some well-known «conventional» wetland subtype classification. However, typology made on the base of West Siberian field studies were found to be the most appropriate for this exact region.

- Revised: «The classification were adapted from numerous national studies (Katz and Neishtadt, 1963; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompassed wooded, patterned, open wetlands and water bodies.»

7 P:20154, L-7: " image classification on a scene by scene basis, regrouping of the derived wetland complex" : What were the wetland classes initially obtained from the maximum likelihood classifier that you have regrouped into the 9 classes as described in table 1? How you extracted this information from the scenes? Could you elaborate?

Main criteria for training data is that the training samples must be homogeneous; land-cover mixtures and heterogeneous areas are avoided. However, wetlands usually occupy a continuum, for example, RHC with small hollows change to RHC with middle and then to one with large hollows. All three RHC types have its own spectral signatures. So initially, we designated three RHC complexes and then joined them into the single class «RHC», because their accuracies were lower than the accuracy of combined class. The same procedure was done for many wetland complex subtypes, some of them: patterned fens, patterned fens with waterlogged hollows, palsa, palsa-hollow, swamps, fens with sparse trees, ryams with hollows, ryams with high and low trees, open fens with *Carex rostrata*, with *Menyanthes trifoliata* and with *Carex aquatilis*, etc.

We have extracted the information from the scenes using high-resolution images (1-3 m) available from Google Earth; we also used our extensive field data recorded in 28 test areas. In addition, during the classification process, the Bhattacharyya distance measure was calculated to check the separability between pairs of classes. Classes that are close by environmental parameters usually have relatively low separability; such classes were combined into the single one. We elaborated it for clarity:

- «However, wetland ecosystems generally have sizes from a few to hundreds of meters and cannot be directly distinguished using Landsat imagery with 30-meter resolutions. Therefore, we developed a second wetland typology that involves 9 mixed "wetland complexes" composing wetland ecosystems in different proportions (Fig. 1; Table 2).»
- «Each wetland complex represents integral class containing several subtypes differing in vegetation composition and structure. Subtypes were mapped using Landsat images and then generalized into final 9 wetland complexes basing upon ecosystem similarity and spectral separability.»
- «The Bhattacharyya distance was used as a class separability measure.»

8 You have only one data type, i.e., Landsat 7 data and no DEM or any other auxiliary information. How did you incorporated water table information at the landscape scale to characterize wooded wetlands and patterned wetlands?

Water table level and trophic state can be designated by vegetation; it is especially true for wooded wetlands. The latter developed at the most drained places within wetland systems. Moreover, the height of trees in ridges and wooded bogs (ryams) strongly depends on moist conditions in soils: the lower trees, the higher water table level. The exclusion is swamps: they have typical for forests height; they are inundated after snowmelt or heavy rain periods and almost dry after droughts; but their areas are small. Thus, the presence (or absence) and height of trees reflects water table level in most cases; both parameters are reflected at multispectral Landsat images. For this goal, near and shortwave infrared channels are the most useful. Some vegetation indices (green-red or normalized difference vegetation indices) can be used to distinguish wetlands with different tree coverage, too.

In other words, open and wooded wetlands have different water level => they have different vegetation => they have different spectral signatures, the latter can be easily separated. Patterned wetlands are a mixture between open and wooded wetlands, but they have very distinct spectral signatures when areas of ridges and hollows are approximately equal.

Water table information in patterned wetlands is taken into account through the estimation ridge/hollow ratios using high-resolution images (1-3 m). Water table information in homogeneous wetlands is taken into account through mapping vegetation by Landsat. In addition, we have made more than 1500 measurements of water table level within 28 test sites in taiga zone. However, water table level data are not necessary for methane emission inventory, because methane flux dataset indirectly contains this information (water table level determines methane emission).

- We have added this information to the Table 1 from the paper to make wetland ecosystem description comprehensive.
- Added text: «The concept of wetland ecosystems has merits for CH4 emission inventory. Methane emission depends mainly on water table level, temperature, and trophic state (Dise et al., 1993; Dunfield et al., 1993; Conrad, 1996). We take into consideration temperature, when we upscale fluxes separately for southern, middle and northern taiga. We take into consideration trophic state, when we map wetland complexes using multispectral Landsat images. We take into consideration water table level, when we map vegetation of wetland ecosystems with high-resolution images, because vegetation reflects soil moisture conditions. We do not directly consider smallest spatial elements as hummocks and tussocks. This omission introduces some uncertainty in regional CH4 emission estimate, which was evaluated by (Sabrekov et al., 2014). Accordingly, reliable estimate of CH4 fluxes accounting for fine spatial detail requires large number of measurements. Such heterogeneity is being addressed by measuring fluxes in all microforms in the field and then obtaining probability density distributions.»

9 L-14: what thresholding methods, please describe P:20155,

Threshold approach means that all pixels below certain value will be assigned to first class (e.g. «wetland»), while the rest of pixels will be assigned to another class (e.g. «non-wetland»). «Thresholding method» is incorrect term, so we have changed it.

- Revised: «Because the WSL vegetation includes various types of forests, meadows, burned areas, agricultural fields, etc., wetland environments were first separated from other landscapes to avoid misclassification. We used thresholds of the Green-Red Vegetation Index (Motohka et al., 2010) to separate majority of wetlands and forests. Thresholds of the 5th Landsat channel (1.55-1.75 µm) was used to mask water bodies and many inundated areas (even vegetated) with the water level up to a few cm below the soil surface. Thresholds were empirically determined for each scene by testing various candidate values.»

10 L-4: What is the resolution of your ground truth data from the Google Earth?

- Revised: «…As a result, we had to rely mostly on high-resolution images available from Google Earth. They came from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics; multispectral images were reduced to visible bands (blue, green, red) and had spatial resolution of 1-3 meters.»

11 L-9: hummocks are totally missing in your entire paper

We understand hummock as low mounds rising from the surface of the bog according to (Nungesser, 2003). Average dimensions of hummocks measured in central Maine peatlands were 2.0m × 3.0m × 0.34m high (Nungesser, 2003). Rochefort et al. (1990) reported dimensions of 18 hummocks in a Canadian bog as 160 cm × 90 cm × 28 cm high. Thus, the size of hummocks is insufficient for mapping them neither by Landsat nor by high-resolution images. Moreover, hummocks are not wide spread in West Siberia; they can be found mainly in open bogs, which occupy less than 5% of WSL wetland area. Hummocks are not areas intensively producing methane, so they are not important at the regional scale. Nevertheless, we indirectly considered them when we had measured methane fluxes in all microforms including hummocks and then obtained probability density distributions of fluxes.

- Now, we have mentioned hummocks in Table 2. Revised: «Open bogs are widespread at the periphery of wetland systems. They are characterized by presence of dwarf shrubs-sphagnum hummocks up to 30 cm in height and 50-200 cm in size.»
- «The concept of wetland ecosystems has merits for CH4 emission inventory… We do not directly consider smallest spatial elements as hummocks and tussocks. This omission introduces some uncertainty in regional CH4 emission estimate, which was evaluated by (Sabrekov et al., 2014). Accordingly, reliable estimate of CH4 fluxes accounting for fine spatial detail requires large number of measurements. Such heterogeneity is being addressed by measuring fluxes in all microforms in the field and then obtaining probability density distributions.»

12 But as per your convention you have in table 1, how did you define the boundary conditions for RHCs and RHLCs within the pixel of your satellite data?

The boundary conditions between classes were mathematically calculated using maximum likelihood algorithm during the classification process basing upon assigned training areas. Surely, wetlands usually occupy a continuum with no clustering into discrete units, so the final boundary between classes is always an assumption. However, the exact boundaries between classes are of little consequence. When complexes are already mapped on the certain image, it is easy to calculate exact area of wetland ecosystems within them using high-resolution (1-3 m) images. Strictly speaking, estimate of lake area coverage in RHLC is not a prior to wetland complex area calculation, but a posterior.

13 P:20155, L-10: Methane emission varies within a small spatial distance of few meters within the peatland as a result of differences in surface structure and functional traits of the vegetation and microforms differ greatly in ecosystem processes. For example, methane (CH4) emissions can vary by two to four-fold across microforms that may be separated by only a few metres (Moore et al.,1990; Huttunen et al.,2003; Kettunen 2002). This means that a pixel resolution of 30 m will not capture such fine scale variations, hence any attempt to estimate methane budget from a coarse resolution data such as yours would introduce bias from the start.

Surely, methane emission varies significantly. To catch all variability, we made many measurements and then obtained probability density distributions of methane fluxes for each wetland ecosystem type in every climate zone. Each probability density distribution was further applied to estimate methane emission. They allow taking into account all spatial variability of methane fluxes. Therefore, minimal spatial unit in our inventory is wetland ecosystem type (ridge, hollow, ryam, etc.).

The conception of wetland ecosystem typology seems to be reasonable, because methane emission depends mainly on water table level, temperature, and trophic state. We take into consideration temperature, when we upscale measurements separately for different natural-climatic zones (south, middle, north taiga, etc.). Water table level and trophic state are reflected by vegetation. When we map wetland complexes and ecosystems, actually we map the vegetation at different scales, 30 m Landsat, and 1-3 m high-resolution images, respectively. Therefore, our mapping and flux measuring efforts can be combined without introducing bias from the start.

We do not consider any spatial units within wetland ecosystems. Surely, this approach introduces some uncertainty in regional estimate, which was calculated in (Sabrekov et al., 2014). However, we do not have methane flux data to provide reliable estimates on higher spatial scale. As it was reported by (Sabrekov et al., 2013), we need more than 90-120 flux measurements to represent spatial variability in each wetland ecosystem in every climate zone. If the inventory were more detail, the number of required measurements would grow exponentially.

- We have added this paragraph to the end of «Wetland typology development» section (see P. 21. L.5-17 in the responce): «The concept of wetland ecosystems has merits for CH4 emission inventory...»

14 P:20155, L-27: What are the other ecological functions you are referring to for upscaling?

For example, GHG inventories (CO_2, CH_4, N_2O CO), carbon balance, NEE, biomass, NPP, peat storage, spatiotemporal dynamics of wetlands (Zimmermann and Kaplan, 2016), models of regional hydrology (Baird et al., 2012; Bohn et al., 2007).

- Added to the end of «Introduction»: «The objectives were: first, to develop a consistent land cover of wetland classes and its structural components; second, to provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, net ecosystem exchange, biomass, etc) and validation of the process models.»

15 P:20160: why these sections are part of the Results section?

This section describes peculiarities of the spatial distribution of different wetland complexes within West Siberia. It is in «Results and Discussion» section, because the description is based on the developed wetland map. In global and regional studies, West Siberia is considered as single ecoregion, which is, surely, true. However, we wanted to highlight its regional peculiarities, which can be interesting and useful for non-local scientists. In this study, we made a «geographical» product, so it is reasonable to describe general patterns.

16 P:20162, L-1: " However the small areas do not make substantial: : :." if you coalesce all the small pools then the contribution of methane emissions could become significant at the landscape scale.

It was obtained using both chamber and bubble trap measurements that methane fluxes in pools, ponds and lakes from middle taiga to the north are less than 0.5 $mgCH_4/m^2/h$ (Repo et al., 2007). Therefore, their impact to the regional emission may not be significant. Concerning their area, the accuracy of lake mapping is actually highest (see confusion matrix, Table 4), because they have the most distinct spectral signatures with low values in 5th Landsat TM channel. Under «Many of the errors were also arranged along the tundra boundary…» we mainly meant errors in palsa complexes, which are similar with typical for this area sparse pine forests with dense lichen layer. Palsa hillocks do not influence on methane emission estimation because of very low (sometimes negative) fluxes. We apologize for inaccuracy!

- Revised: «In addition, many errors happened along the tundra boundary caused by the lack of ground truth data combined with the high landscape heterogeneity. However, those small areas mainly correspond to palsa complexes and have slight impact on CH4 flux estimate.»

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Mapping of West Siberian taiga wetland complexes using Landsat imagery: Implications for methane emissions

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Abstract

High latitude wetlands are important for understanding climate change risks because these environments sink carbon dioxide and emit methane. Fine-scale heterogeneity of wetland landscapes poses a serious challenge when generating regional-scale estimates of greenhouse gas fluxes from point observations. To reduce uncertainties at the regional scale, we mapped wetlands and water bodies in the taiga zone of The West Siberia Lowland (WSL) on a scene-by-scene basis using a supervised classification of Landsat imagery. Training data consists of high-resolution images and extensive field data collected at 28 test areas. The classification scheme aims at supporting methane inventory applications and includes 7 wetland ecosystem types comprising 9 wetland complexes distinguishable at the Landsat resolution. To merge typologies, mean relative areas of wetland ecosystems within each wetland complex type were estimated using high-resolution images. Accuracy assessment based on 1082 validation polygons of 10×10 pixel size indicated an overall map accuracy of 79%. The total area of the WS wetlands and water bodies was estimated to be 52.4 Mha or 4-12% of the global wetland area. Ridge-hollow complexes prevail in WS's taiga zone accounting for 33% of the total wetland area, followed by pine bogs or "ryams" (23%), ridge-hollow-lake complexes (16%), open fens (8%), palsa complexes (7%), open bogs (5%), patterned fens (4%), and swamps (4%).

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Удалено: Fine scale heterogeneity of wetland landscapes pose challenges for producing the greenhouse gas flux inventories based on point observations

Удалено: recorded

Удалено: in

Удалено: The training dataset was based on high-resolution images and field data that were collected at 28 test areas

Удалено: developed

Удалено: Classification scheme was aimed at methane inventory applications and included 7 wetland ecosystem types composing 9 wetland complexes in different proportions

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Various oligotrophic environments are dominant among wetland ecosystems, while poor fens cover only 14% of the area. Because of the significant change in the wetland ecosystem coverage in comparison to previous studies, a considerable reevaluation of the total CH_4 emissions from the entire region is expected. A new Landsat-based map of WS's taiga wetlands provides a benchmark for validation of coarse-resolution global land cover products and wetland datasets in high latitudes.

1 Introduction

High latitude wetlands are important for understanding climate change mechanism as they provide long term storage of carbon and emit significant amount of methane. The West Siberia Lowland (WSL) is the world's largest high-latitude wetland system and experiences an accelerated rate of climate change (Solomon et al., 2007).

Poorly constrained estimates of wetland and lake area constitute a major uncertainty in estimating current and future greenhouse gas emissions (Melton et al., 2013; Turetsky et al., 2014; Petrescu et al., 2010). Although wetland extent in WSL has been reasonably well captured by global products based on topographic maps (Lehner and Döll, 2004; Matthews and Fung, 1987), fine-scale heterogeneity of WSL's wetland landscapes (Bohn et al., 2007) requires adding fine scale information in ecosystem functioning as made in wetland CH_4 emission inventory (Glagolev et al., 2011) and estimates of net primary production (Peregon et al., 2008). Present land cover products fail to capture fine-scale spatial variability within WSL's wetlands because of lack of detail necessary for reliable productivity and emissions estimates. Frey and Smith (2007) mentioned insufficient accuracy of four global vegetation and wetland products with the best agreement of only 56% with the high-resolution WSL Peatland Database (WSLPD) (Sheng et al., 2004). Some products (Schroeder et al., 2010; Papa et al., 2010) tend to map only inundation, overlooking areas of «unsaturated» wetlands where the water table is below the moss cover. Because boreal peatlands does not experience prolonged inundation, such products underestimate their area (Krankina et al., 2008). Uncertainty in wetland inventory results in severe biases in CH_4 emission estimates, the scale of differences has been shown by Bohn et al. (2015).

Modelers simulating methane emission are in need for high-resolution wetland maps that do not only delineate wetlands but also identify the major sub-types to which different environmental parameters could potentially be applied (Bohn et al., 2015). Several wetland

- **Удалено:** the
- **Удалено:** mesotrophic
- **Удалено:** update
- **Удалено:** West Siberia (WS) is the world's largest high-latitude wetland system situating in the high latitudes experiencing accelerated rate of climate change
- **Удалено:** It was found both at global and regional scales that poorly constrained estimates of wetland and lake area is a major uncertainty in predicting current and future of greenhouse gas budget
- **Удалено:** (Matthews and Fung, 1987; Lehner and Doll, 2004)
- **Удалено:** (Eppinga, 2010 #849)(Bridgham, 2013 #276)
- **Удалено:** on fine scale heterogeneity
- **Удалено:** Fine-scale heterogeneity of WSL's wetland landscapes Fine scale heterogeneity of WS wetland landscapes (Bohn et al., 2007; Eppinga et al., 2010; Bridgham et al., 2013) is not accurately accounted for when wetland CH_4 emission inventories pose challenges for producing inventories of methane emissions (Glagolev et al., 2011) and wetland net primary production (Peregon et al., 2008) are generated from point-scale field observationswhich are based on large number of point scale field measurements.. ¶
- **Удалено:** usually
- **Удалено:** (ESA map, Krankina/NELDA map?)
- **Удалено:** failed to capture the fine-scale
- **Удалено:** WS wetland maps
- **Удалено:** for
- **Удалено:** (Papa, 2010 #360)(Prigent, 2007 #449)
- **Удалено:** surface water
- **Удалено:** Coarse-resolution products tend to underestimate the wetland area when the water table is a few centimetres below the moss cover, resulting in the conclusion that surface is not saturated with water
- **Удалено:** .
- **Удалено:** Bohn et al, (2015)
- **Удалено:** Modellers
- **Удалено:** should be able to draw upon
- **Удалено:** a global
- **Удалено:** es
- **Удалено:** identifies

maps have been used to define the wetland extent in WSL, however their application to net primary production (NPP) and methane emission inventories was accompanied by difficulties due to crude classification scheme, limited ground truth data and low spatial resolution. One peatland typology map that distinguishes several vegetation and microtopography classes and their mixtures was developed at the State Hydrological Institute (SHI) by Romanova et al. (1977). Peregon et al. (2005) digitized and complemented this map by estimating the fractional coverage of wetland structural components using Landsat images and aerial photographs for five test sites. However, the limited amount of fractional coverage data and coarse resolution still result in large uncertainties in upscaling methane fluxes (Kleptsova et al., 2012).

Our goal was to develop a multi-scale approach for mapping wetlands using Landsat imagery with a resolution of 30 m so the results could better meet the needs of land process modelling and other applications concerning methane emission from peatlands. In this study, the WSL taiga zone was chosen as the primary target for the land cover classification due to wetland abundance. The objectives were: first, to develop a consistent land cover of wetland classes and its structural components; second, to provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, net ecosystem exchange, biomass, etc) and validation of the process models.

2 Materials and Methods

2.1 Study Region

The West Siberian Lowland is a geographical region of Russia bordered by the Ural Mountains in the west and the Yenisey River in the east; the region covers 275 Mha within 62-89°E and 53-73°N. Because of its vast expanse and flat terrain, the vegetation cover of the Lowland shows clear latitudinal zonation. According to Gvozdetsky (1968), the taiga zone is divided into three geobotanical subzones: northern taiga, middle taiga and southern taiga. Taiga corresponds to the raised string bog province and covers about 160 Mha in the central part of the WS. It is characterized by flat terrain with elevations of 80 to 100 m above sea level rising to about 190 m in the «Siberian Uvaly» area. Average annual precipitation is about 450-500 mm and evaporation is 200-400 mm (National Atlas of Russia, 2008). The excess water supply and flat terrain with poor drainage provides favorable conditions for wetland formation. Comprehensive

Удалено: strong generalization of classes

Удалено: Various wetland maps have been used to define the wetland extent in WS, however simplistic classification schemes in aggregate to limited or no ground truth data and strong generalization of classes diminish their applicability

Удалено: or wetland ecosystems

Удалено: digitized and complemented this map by estimating the fractional coverage of wetland structural components or wetland ecosystems using Landsat and high-resolution images for five test sites.

Удалено: lead to

Удалено: However, the limited amount of fractional coverage data and coarse resolution introduce large uncertainties in scaled-up estimations

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Удалено: to understand the spatial distribution of different wetlands and their linkage with other land units; and third,

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Удалено: region

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Удалено: stretching

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Удалено: topography

Удалено: topography

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Удалено: favourable

Удалено: Large fraction of the area, including watersheds and floodplains, is waterlogged. The hydrographic structure of this zone differs from the northern and southern parts of the WS. The largest peatlands are most typical of the central flat parts of the watersheds where, together with forests, they comprise the zonal vegetation and cover vast territories (Solomeshch, 2005).

synthesis of Russian literature regarding the current state of the WSL peatlands, their development and sensitivity to climatic changes was made by Kremenetski et al. (2003).

2.2 Classification methodology

No single classification algorithm can be considered as optimal methodology for improving vegetation mapping; hence, the use of advanced classifier algorithms must be based on their suitability for achieving certain objectives in specific applications (Adam et al., 2009). Because mapping over large areas typically involves many satellite scenes, multi-scene mosaicking is often used to group scenes into a single file set for further classification. This approach optimizes both the classification process and edge matching. However, large multi-scene mosaicking has essential drawback when applying to highly heterogeneous WSL wetlands. It creates a variety of spectral gradients within the file (Homer and Gallant, 2001), especially when the number of the appropriate scenes is limited. It results in spectral discrepancy that is difficult to overcome. In this study, the advantages of consistency in class definition of the scene-by-scene classification approach were considered to outweigh the inherent disadvantages of edge matching and processing labor. Thus, our entire analysis was performed on a scene-by-scene basis, similarly to efforts by Giri et al. (2011) and Gong et al. (2013).

For land cover consistency, data of the same year and season, preferably of the growing season peak (July) are required. However, the main complication was the low availability of good quality cloudless images of WSL during those periods. Scenes collected earlier than the 2000s were very few, so they were used as substitutes for places where no other suitable imagery could be found. Landsat-7 images received after 2003 were not used due to data gaps, while Landsat-8 was launched after the starting our mapping procedure. Finally, we collected 70 suitable scenes during the peak of the growing seasons in different years. Majority of the images were Landsat 5 TM scenes from July 2007. The scene selection procedure was facilitated by the ability of smoothing the slight inconsistencies between images by specifying training sites in overlapping areas.

The overall work flow involves data pre-processing, preparation of the training and test sample collections, image classification on a scene-by-scene basis, regrouping of the derived classes into 9 wetland complexes, the estimation of wetland ecosystem fractional coverage and accuracy assessment. Atmospheric correction was not applied because this process is unnecessary as long as the training data are derived from the image being classified (Song et

Удалено: WS

Удалено: The study summarizes information about WS geology, hydrology, climate, vegetation, and peatland zonation. Basing on existing Russian data, authors found that the mean depth of peat accumulation in the WSL is 256 cm and the total amount of carbon stored there may exceed 54×10^9 metric tons.

Удалено: WS

Удалено: with same season with similar vegetation and hydrological conditions

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Удалено: The scene selection procedure was facilitated by the possibility of adequately smoothing the slight inconsistencies between images by specifying training sites in overlapping areas.

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al., 2001). All of the images were re-projected onto the Albers projection. Because the WSL vegetation includes various types of forests, meadows, burned areas, agricultural fields, etc., wetland environments were first separated from other landscapes to avoid misclassification. We used thresholds of the Green-Red Vegetation Index (Motohka et al., 2010) to separate majority of wetlands and forests. Thresholds of the 5th Landsat channel (1.55-1.75 µm) was used to mask water bodies and many inundated areas (even vegetated) with the water level up to a few cm below the soil surface. Thresholds were empirically determined for each scene by testing various candidate values. Masked Landsat images were filtered in MATLAB v.7.13 (MathWorks) to remove random noise and then classified in Multispec v.3.3 (Purdue Research Foundation) using a supervised classification method. The maximum likelihood algorithm was used because of its robustness and availability in almost any image-processing software (Lu and Weng, 2007). All Landsat bands except the thermal infrared band were used.

Training data plays a critical role in the supervised classification technique. Representative data preparation is the most time-consuming and labour-intensive process in regional scale mapping efforts (Gong et al., 2013). As a primary source of information, we used the extensive dataset of botanical descriptions, photos, pH and electrical conductivity data from 28 test sites in WSL (Glagolev et al., 2011). Due to vast expanse and remoteness of WSL, we still had a lack of the ground truth information, which hampered training dataset construction. As a result, we had to rely mostly on high-resolution images available from Google Earth. They came from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics; multispectral images were reduced to visible bands (blue, green, red) and had spatial resolution of 1-3 meters. The processing started with mapping scenes where ground truth data and high-resolution images are extensively available, so the classification results could be checked for quality assurance; mapping continued through adjacent images and ended at the less explored scenes with poor ground truth data coverage.

To collect training data most efficiently, we used criteria similar to those used by (Gong et al., 2013) for training sample selection: (i) the training samples must be homogeneous; mixed land-cover and heterogeneous areas are avoided; and (ii) all of the samples must be at least 10 pixels in size with an average sample area of approximately 100-200 pixels. The Bhattacharyya distance was used as a class separability measure. The classifier was designed using training samples and then evaluated by classifying input data. The percentage of misclassified samples was taken as an optimistic predication of classification performance (Jain et al., 2000). When

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Удалено: Due to the remoteness of WS, we have a lack of ground truth information, which hampers training dataset construction. As a result, we were constrained to base training sample selections mostly on high-resolution imagery available in Google Earth.

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Удалено:) and resolution of 1-3 meters, were used

Удалено: However there were no meta-data available regarding image acquisition dates and spectral transformations. As an additional source of information, Our field knowledge comprising 8 years of fieldwork in West Siberia, which resulted in an we used an extensive dataset of botanical descriptions, field photos, and pH and electrical conductivity data from 28 test sites in WSL (Glagolev et al., 2011).

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accuracy of more than 80% across the training set was attained with no fields showing unreasonable or unexplainable errors, the classification process was started. Classification mismatch between scenes was minimized by placing training samples in overlapping areas. Combining the classified images and area calculations were made using GRASS module in Quantum GIS. Noise filter was applied to eliminate objects smaller than 2×2 pixels. After that, a 10×10-pixel moving window was used to determine the dominant class, which was further assigned to the central 4×4-pixel area.

2.3 Wetland typology development

As a starting point for the mapping procedure, a proper classification scheme is required. Congalton et al. (2014) showed that the classification scheme alone may result in largest error contribution and thus deserves highest implementation priority. Its development should rely on the study purposes and the class separability of the input variables. In our case, wetland mapping was initially conceived as a technique to improve the estimate of the regional CH_4 emissions and, secondarily, as a base to upscale other ecological functions. WSL wetlands are highly heterogeneous, however, within each wetland complex we can detect relatively homogeneous structural elements or "wetland ecosystems" with similar water table levels (WTL), geochemical conditions, vegetation covers and, thus, rates of CH_4 emissions (Sabrekov et al., 2013). To ensure a reliable upscaling, we assigned 7 wetland ecosystems in our classification scheme (Fig. 1; Table 1).

However, wetland ecosystems generally have sizes from a few to hundreds of meters and cannot be directly distinguished using Landsat imagery with 30-meter resolutions. Therefore, we developed a second wetland typology that involves 9 mixed "wetland complexes" composing wetland ecosystems in different proportions (Fig. 1; Table 2). The classification were adapted from numerous national studies (Katz and Neishtadt, 1963; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompassed wooded, patterned, open wetlands and water bodies. The criteria for assigning wetland complexes were: (i) separability on Landsat images, and (ii) abundance in the WSL taiga zone. Each wetland complex represents integral class containing several subtypes differing in vegetation composition and structure. Subtypes were mapped using Landsat images and then generalized into final 9 wetland complexes basing upon ecosystem similarity and spectral separability.

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The spectral classes that were discriminated during the supervised classification were generalized into 9 wetland complexes.

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Удалено: until satisfactory results were achieved

Удалено: Because temporal differences exist among the scenes, patch effects can be slightly observed.

Удалено: spots

Удалено: Wetlands and water bodies that are only one or a few Landsat pixels in size exist, and some of these sites may be random image noises. Therefore, firstly we applied noise filter to eliminate objects smaller than 2×2 pixels. Then, a 10×10-pixel mobile window was used to determine the dominant class, which was further assigned to the central 4×4-pixel.

Удалено: Therefore, a simple low pass filter was applied to eliminate such objects.

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Удалено: with highly variable water table levels (WTL), geochemical conditions, vegetation covers, etc.

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To merge typologies, we estimated relative areas of wetland ecosystems within each wetland complex of the final map. Depending on heterogeneity, 8 to 27 test sites of 0.1-1 km^2 size were selected for each heterogeneous wetland complex. High-resolution images of 1-3 m resolution corresponding to these areas were classified in Multispec v.3.3 using visible channels. An unsupervised ISODATA classification was done on the images specifying 20 classes with a convergence of 95%. Obtained classes were manually reduced to seven wetland ecosystem types. Their relative proportions were calculated and then averaged among the test sites.

Thus, we used multiscale approach relying in two typologies. First, typology of wetland complexes was used for mapping Landsat images; second, typology of wetland ecosystems was used for upscaling CH_4 fluxes. The approach is similar to one devised by Peregon et al. (2005), where relative area proportions of "micro-landscape" elements within SHI wetland map were used for NPP data upscaling.

During wetland typology development, we made several assumptions. Firstly, the wetland complexes were considered as individual objects, while they actually occupy a continuum with no clustering into discrete units. Secondly, we assumed that all of the wetland water bodies originated during wetland development have sizes less than 2×2 Landsat pixels. They are represented by wetland pools and waterlogged hollows, which are structural components of RHLC. The rest of the water bodies were placed into the "Lakes and rivers" class. Thirdly, in this study, we only consider peatlands and water bodies; floodplain areas were separated from wetlands during the classification process.

The concept of wetland ecosystems has merits for CH_4 emission inventory. Methane emission depends mainly on water table level, temperature, and trophic state (Dise et al., 1993; Dunfield et al., 1993; Conrad, 1996). We take into consideration temperature, when we upscale fluxes separately for southern, middle and northern taiga. We take into consideration trophic state, when we map wetland complexes using multispectral Landsat images. We take into consideration water table level, when we map vegetation of wetland ecosystems with high-resolution images, because vegetation reflects soil moisture conditions. We do not directly consider smallest spatial elements as hummocks and tussocks. This omission introduces some uncertainty in regional CH_4 emission estimate, which was evaluated by (Sabrekov et al., 2014). Accordingly, reliable estimate of CH_4 fluxes accounting for fine spatial detail requires large number of measurements. Such heterogeneity is being addressed by measuring fluxes in all microforms in the field and then obtaining probability density distributions.

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Удалено: To yield reliable upscaling, we assigned 7 wetland ecosystems in our classification scheme (Fig. 1):¶
"Water": all water bodies greater than 2×2 Landsat pixels;¶
"Waterlogged hollows": water bodies fewer than 2×2 Landsat pixels or depressed parts of wetland complexes with WTLs above the average moss/vegetation surface;¶
"Oligotrophic hollows": depressed parts of bogs with WTLs beneath the average moss/vegetation cover;¶
"Ridges": long and narrow elevated parts of wetland complexes with dwarf shrubs-sphagnum vegetation cover;¶
"Ryams": extensive pine-dwarf shrubs-sphagnum peatland areas;¶
"Fens": integrated class for various types of rich fens, poor fens and wooded swamps;¶
"Palsa hillocks": elevated parts of palsa complexes with permafrost below the surface.¶

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Удалено: the evaluation of the area fraction occupied by

Удалено: within patterned wetlands was based on aerial

Удалено: were forced to

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Удалено: defining wetland complex isminor importance

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Удалено: peatland

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3 Results and Discussion

3.1 Wetland map

Based on Landsat imagery, we developed a high-resolution wetland inventory of the WSL taiga zone (Fig. 2). The total area of wetlands and water bodies was estimated to be 52.4 Mha. West Siberian taiga wetlands are noticeable even from global prospective. The global total of inundated areas and peatlands was estimated to cover from 430 (Cogley, 1994) to 1170 Mha (Lehner and Döll, 2004) as summarized by Melton et al. (2013); therefore, taiga wetlands in WSL account for approximately from 4 to 12% of the global wetland area. Their area is larger than the wetland areas of 32.4, 32, and 41 Mha in China (Niu et al., 2012), Hudson Bay Lowland (Cowell, 1982) and Alaska (Whitcomb et al., 2009), respectively. The extent of West Siberia's wetlands exceeds the tropical wetland area of 43.9 Mha (Page et al., 2011) emphasizing the considerable ecological role of the studied region.

As summarized by Sheng et al. (2004), the majority of earlier Russian studies estimated the extent of the entire WS's mires to be considerably lower. These studies probably inherited the drawbacks of the original Russian Federation Geological Survey database, which was used as the basis for the existing WSL peatland inventories (Ivanova and Novikova, 1976). This database suffered from lack of field survey data in remote regions, a high generalization level and only considered economically valuable peatlands with peat layers deeper than 50 cm.

Our peatland coverage is similar to the estimate of 51.5 Mha (Peregon et al., 2009) by SHI map (Romanova et al., 1977). However, a direct comparison between the peatland maps shows that the SHI map is missing important details on the wetland distribution (Fig. 3). SHI map was based on aerial photography, which was not technically viable for full and continuous mapping of a whole region because it is too costly and time-consuming to process (Adam et al., 2009).

Distribution of wetland ecosystem areas have changed significantly in comparison to SHI map (Peregon et al., 2009); in particular, we obtained 105% increase in spatial extent of CH_4 high-emitting ecosystems such as waterlogged, oligotrophic hollows and fens. In the case study of WS's middle taiga, we found that applying the new wetland map led to a 130% increase in the CH_4 flux estimate from the domain (Kleptsova et al., 2012) in comparison with the estimate based on SHI map. Thus, a considerable revaluation of the total CH_4 emissions from the whole region is expected.

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Удалено: feasible
Удалено: mapping and monitoring wetland vegetation on a regional scale
Удалено: The satellite-based classifications tend to identify many small peatlands and their subgroups, which are ignored in the more generalized SHI map. However, the satellite classifications also delineate small gaps within contiguous peatlands. The net result of both effects is a fortuitous cancellation of their differences (Sheng et al., 2004), leaving the discrepancy in the spatial distributions. The latter is essential for environmental parameter upscaling purposes.
Удалено: In addition,
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3.2 Regularities of zonal distribution

WS has a large variety of wetlands that developed under different climatic and geomorphologic conditions. Concerning the wetland complex typology (excluding "Lakes and rivers" class), RHCs prevail in WS's taiga, accounting for 32.2% of the total wetland area, followed by pine bogs (23%), RHLCs (16.4%), open fens (8.4%), palsa complexes (7.6%), open bogs (4.8%), patterned fens (3.9%) and swamps (3.7%). Various bogs are dominant among the wetland ecosystems (Table 3), while fens cover only 14.3% of the wetlands. Waterlogged hollows and open water occupy 7% of the region, which is similar to the estimate by Watts et al. (2014), who found that 5% of the boreal-Arctic domain was inundated during summer season.

The individual wetland environments have a strongly pronounced latitudinal zonality within the studied region. Zonal borders stretch closely along latitude lines, subdividing the taiga domain into the southern, middle, and northern taiga subzones (Fig. 2, black lines). To visualize the regularities of the wetland distribution, we divided the entire area into 0.1°×0.1° grids and calculated ratios of wetland ecosystem areas to the total cell areas for each grid (Fig. 4) using fractional coverage data from Table 2.

Mire coverage of WSL's northern taiga (62-65°N) is approximately 36%. Because of the abundance of precipitation, low evaporation and slow runoff, the northern taiga is characterized by largest relative area of lakes and waterlogged hollows, covering a third of the domain (Fig. 4a, b). Vast parts of the zone are occupied by the peatland system "Surgutskoe Polesye," which stretches for one hundred kilometers from east to west between 61.5°N and 63°N. Peatland and water bodies cover up to 70% of the territory, forming several huge peatland-lake complexes divided by river valleys. Northward, the slightly paludified "Sibirskie Uvaly" elevation (63.5°N) divides the northern taiga into two lowland parts. Palsa hillocks appear in the "Surgutskoe Polesye" region and replace the ridges and ryams to the north of the "Sibirskie Uvaly" region (Fig. 4f).

RHCs are the most abundant in the middle taiga (59-62°N), where mires occupy 34% of the area. Large wetland systems commonly cover watersheds and have a convex dome with centres of 3-6 m higher than periphery. These environments have peat layer of several meters depth composed of sphagnum peat with the small addition of other plants. The wetland ecosystems here have distinct spatial regularities. Central plateau depressions with stagnant water are covered by RHLCs. Different types of RHCs cover better-drained gentle slopes. The most

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Удалено: occupying
Удалено: domain
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Удалено: average
Удалено: estimation
Удалено: with surface water
Удалено: the non-frozen
Удалено: The knowledge regarding the spatial distribution of different wetlands facilitates mapping and further understanding of their linkage with each other and other land units.
Удалено: the
Удалено: ratios
Удалено: 1
Удалено: A slight patch effect that ensues from the scene-by-scene classification technique is observed. Abrupt leaps correspond to classification errors and indicate less accurate map patches, which can be improved by more careful image acquisition.
Удалено: WS's northern taiga (approximately 62-65°N) has approximately 36% mire coverage.
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Удалено: minimal evaporation, and scanty runoff
Удалено: characterised
Удалено: corresponds to the maximal distribution of
Удалено: kilometres
Удалено: for a hundred kilometres
Удалено: and is located
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drained areas are dominated by ryams. Poor and rich fens develop along wetland's edges with relatively high nutrient availability. Wooded swamps usually surround vast wetland systems.

The wetland extent reaches 28% in WS's southern taiga area (56-59°N). Wetlands are composed of raised bogs alternating with huge open and patterned fens. The eastern part of the subzone is dominated by small and medium-sized wetland complexes. The southern and middle taiga wetlands exhibit similar spatial patterns; however, the area of fens increases southwards due to the abundance of carbonate soils and higher nutrient availability. Velichko et al. (2011) provide evidence for existence of a vast cold desert in the northern half of the WSL at the late glacial time, whereas the southernmost part was an area of loess accumulation. The border between fen and bog-dominated areas extends near 59°N and corresponds to the border between the southern and middle taiga zones (Fig. 4c and e).

3.3 Accuracy assessment

The map accuracy assessment was based on 1082 validation polygons of 10×10 pixels that were randomly spread over the WSL taiga zone. We used high-resolution images available in Google Earth as the ground truth information. The confusion matrix (Table 4) was used as a way to represent map accuracy (Congalton and Green, 2008). Overall, we achieved the classification accuracy of 79% that can be considered reasonable for such a large and remote area. We found that the accuracies for different land-cover categories varied from 62 to 99%, with the lake and river, ryam, and RHC class areas mapped most successfully and open bogs and patterned fens being the most confused. Some errors were associated with mixed pixels (33 polygons), whose presence had been recognized by Foody (2002) as a major problem, affecting the effective use of remotely sensed data in per-pixel classification.

Wetland complexes within large wetland systems had the highest classification accuracies. In contrast, the uncertainties are particularly high for small objects. It is of special importance in southern part of the domain, where highly heterogeneous agricultural landscapes neighbour upon numerous individual wetlands of 100-1000 ha area. Several vegetation indices was tested to map them; however, the best thresholding result was achieved by using Landsat thermal band. In addition, many errors happened along the tundra boundary caused by the lack of ground truth data combined with the high landscape heterogeneity. However, those small areas mainly correspond to palsa complexes and have slight impact on CH_4 flux estimate.

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Удалено: Velichko et al. (2011) provided evidence of a vast cold desert in the northern half of WS during the last glacial period, while the southernmost part of the plain was an area of loess accumulation. Now, the border between fen and bog dominated areas extends near 59°N and corresponds to the border between the southern and middle taiga zones (Fig. 4c, e).
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Misclassifications usually occurred between similar classes introducing only a minor distortion in map applications. Patterned fens and open bogs were classified with the lowest producer's accuracy (PA) of 62%. Patterned fens include substantial treeless areas, so they were often misclassified as open fens. They were also confused with RHCs due to the similar "ridge-hollow" structure. Some open bogs have tussock shrub cover with sparsely distributed pine trees provoking misclassification as RHCs and pine bogs. Open fens have higher user's accuracy (UA) and PA; however, visible channels of high-resolution images poorly reflect trophic state, which underrates classification errors between open bogs and open fens. Swamps and palsa complexes have very high PA and low UA, which is related to their incorrect identification in non-wetland areas. Palsa complexes were spectrally close to open woodlands with lichen layer, which covers wide areas of WSL north taiga. During dry period, swamps were often confused with forests, whereas in the field they can be easily identified through the presence of peat layers and a characteristic microrelief. In both cases, more accurate wetland masks would lead to substantially higher accuracy levels. Lakes and rivers were classified the best due to the high spectral separability of the class. They can be confused with RHLCs represented by a series of small lakes or waterlogged hollows alternating with narrow isthmuses. Floodplains after snow melt can also be classified as lakes (11 polygons). RHCs and pine bogs were accurately identified due to their abundance in the study region and high spectral separability.

3.4 Challenges and future prospects

The contrast between vast wetland systems and the surrounding forests is so distinct in WSL that wetlands can be adequately identified by the summer season images (Sheng et al., 2004). On the contrary, correct mapping of wetland with pronounced seasonal variations remains one of the largest challenges. Wetlands become the most inundated after snow melt or rainy periods resulting in partial transformation of oligotrophic hollows and fens into waterlogged hollows (see hollows with brown Sphagnum cover at Fig. 1). Image features of swamps after drought periods become similar to forests. Interannual variability of water table level in WSL wetlands (Schroeder et al., 2010; Watts et al., 2014) also makes impact on mapping results.

New methodologies and protocols are needed to improve our ability to monitor water levels (Kim et al., 2009). Observations of soil moisture and wetland dynamic using radar data such as PALSAR (Chapman et al., 2015; Clewley et al., 2015) and Global Navigation Satellite Signals Reflectometry are promising (Chew et al., 2016; Zuffada et al., 2015). Advanced classification

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techniques such as fuzzy logic can be applied for mapping fine-scale heterogeneity (Adam et al., 2009). Recent innovations in wetland mapping were described by Tiner et al. (2015).

Water table fluctuations are especially important for upscaling CH_4 fluxes because the spatial distribution of methane emissions, and therefore, the total methane emission, are functions of the spatial distribution of water table depths (Bohn et al., 2007). Wetland ecosystems with water levels close to surface contribute most to the regional flux, while the contribution of dryer ecosystems (ryams, ridges and palsa hillocks) is close to negligible (Glagolev et al., 2011; Sabrekov et al., 2014). _ENREF_59

Although the synergistic combination of active and passive microwave sensor data is advantageous for accurately characterizing open water (Schroeder et al., 2010) and wetlands, the remote sensing of water regimes is successful only when in situ data are available for calibration. We still lack in situ measurements of the water table dynamics within WSL wetlands. Limited monitoring have been made at the Bakchar field station (Krasnov et al., 2013; Krasnov et al., 2015) and Mukhrino field station (Bleuten and Filippov, 2008); however, the vast majority of obtained data are not yet analyzed and published. These measurements are of special importance for the northern taiga and tundra, where shallow thermokarst lakes with fluctuating water regimes cover huge areas.

The scarcity of reliable reference data and subsequent lack of consistency also limit the accuracy of maps (Homer and Gallant, 2001). The use of ancillary data can largely improve it (Congalton et al., 2014); however, more reliable classification accuracy comes with significant costs regarding detailed field data. The next step in map improvement should rely on the acquisition of more ground truth data for the poorly classified wetland types and remote regions.

4 Conclusions

Boreal peatlands play a major role in carbon storage, methane emissions, water cycling and other global environmental processes, but better understanding of this role is constrained by the inconsistent representation of peatlands on (or even complete omission from) many global land cover maps (Krankina et al., 2008). In this study, we developed a map representing the state of the taiga wetlands in WSL during the peak of the growing season. The efforts reported here can be considered as an initial attempt at mapping boreal wetlands using Landsat imagery, with the general goal of supporting the monitoring of wetland resources and upscaling the methane

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emissions from wetlands and inland waters. The resulting quantitative definitions of wetland complexes combined with a new wetland map can be used for the estimation and spatial extrapolation of many ecosystem functions from site-level observations to the regional scale. In the case study of WS's middle taiga, we found that applying the new wetland map led to a 130% increase in the CH_4 flux estimation from the domain (Kleptsova et al., 2012) comparing with estimation based on previously used SHI map. Thus, a considerable reevaluation of the total CH_4 emissions from the entire region is expected.

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Удалено: In the case study of WS's taiga, applying a new wetland map led to a significant change in the wetland ecosystem areas comparing to the estimate by Peregon et al. (2009), previously used in our methane inventory (Glagolev et al., 2011).

We estimate a map accuracy of 79% for this large and remote area. The next step in improving mapping quality will depend on the acquisition of ground truth data from the least discernible wetland landscapes and remote regions. Correctly distinguishing wetland complexes with strongly pronounced seasonal variability in their water regimes remains one of the largest challenges. This difficulty can be resolved by installing water level gauge network and usage both combined remote sensing data and advanced classification techniques.

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Our new Landsat-based map of WS's taiga wetlands can be used as a benchmark dataset for validation of coarse-resolution global land cover products and for assessment of global model performance in high latitudes. Although classification scheme was directed towards improving CH_4 inventory, the resulting map can also be applied for upscaling of the other environmental parameters.

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Acknowledgements

We thank Amber Soja and anonymous reviewers for assisting in improving the initial version of the manuscript. This study (research grant No 8.1.94.2015) was supported by The Tomsk State University Academic D.I. Mendeleev Fund Program in 2014-2015. The study was also supported by the GRENE-Arctic project by MEXT Japan.

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Table 1. Wetland ecosystem types

Wetland ecosystem	**Short description**	**WTL, cm (1st/2nd/3rd quartiles)[1]**
Open water	All water bodies greater than 2×2 Landsat pixels	-
Waterlogged hollows	Open water bodies fewer than 2×2 Landsat pixels or depressed parts of wetland complexes with WTLs above the average moss/vegetation surface	-10 / -7 / -4
Oligotrophic hollows	Depressed parts of bogs with WTLs beneath the average moss/vegetation cover	3 / 5 / 10
Ridges	Long and narrow elevated parts of wetland complexes with dwarf shrubs-sphagnum vegetation cover	20 / 32 / 45
Ryams	Extensive pine-dwarf shrubs-sphagnum areas	23 / 38 / 45
Fens	Integrated class for various types of rich fens, poor fens and wooded swamps	7 / 10 / 20
Palsa hillocks	Elevated parts of palsa complexes with permafrost below the surface	Less than 45

[1] Positive WTL means that water is below average moss/soil surface; the data was taken from field dataset (Glagolev et al., 2011)

Удалено: peatland

Table 2. Wetland types and fractional coverage of wetland ecosystems (Open water – W, Waterlogged hollows – WH, Oligotrophic hollows – OH, Ridges – R, Ryams – Ry, Fens – F, Palsa hillocks – P)

Wetland complexes	Short description	Wetland ecosystems
	Wooded wetlands	
Pine-dwarf shrubs-sphagnum bogs (pine bogs, ryams)	Dwarf shrubs-sphagnum communities with pine trees (local name – "ryams") occupy the most drained parts of wetlands. Pine height and crown density are positively correlated with the slope angle. Ryams purely depend on precipitation and the atmospheric input of nutrients. The next evolutionary type under increased precipitation is RHC.	Ry: 100%
Wooded swamps	Wooded swamps develop in areas with close occurrence of groundwater. They frequently surround wetland systems; they can also be found in river valleys and terraces. Wooded swamps are extremely diverse in floristic composition and have prominent microtopography.	F: 100%
	Patterned wetlands	
Ridge-hollow complexes (RHC)	RHC consists of alternating long narrow ridges and oligotrophic hollows. They purely depend on precipitation and the atmospheric input of nutrients. The configuration of ridges and hollows depend on the slope angle and hydrological conditions of the contiguous areas. RHCs with small, medium, and large hollows can be arranged within the class.	R: 42% OH: 58%
Ridge-hollow-lake complexes (RHLC)	RHLCs develop on poorly drained watersheds or after seasonal flooding of patterned wetlands. RHLCs are the most abundant in northern taiga. They may include numerous shallow pools. Hollows can be both oligotrophic and meso- or eutrophic.	R: 31% OH: 25% WH: 31% F: 13%
Patterned fens	Patterned fens are widely distributed within the region. They correspond to the WSL type of aapa mires. Patterned fens are composed of meso- or eutrophic hollows alternating with narrow ridges. The vegetation cover commonly includes sedge-moss communities.	R: 28% F: 72%
Palsa complexes	Palsa complexes are patterned bogs with the presence of palsa hillocks – frost heaves of 0.5-1 height. They arise in the north taiga and prevail northwards. They may include numerous shallow pools.	WH: 12% OH: 37% P: 51%
	Open wetlands	
Open bogs	Open bogs are widespread at the periphery of wetland systems. They are characterized by presence of dwarf shrubs-sphagnum hummocks up to 30 cm in height and 50-200 cm in size.	OH: 100%
Open fens	Open fens are the integral class that encompasses all varieties of open rich and poor fens in WSL taiga. They occupy areas with higher mineral supplies at the periphery of wetland systems and along watercourses. The vegetation cover is highly productive and includes sedges, herbs, hypnum and brown mosses.	F: 100%
	Water bodies	
Lakes and rivers	All water bodies larger than 60×60 m², so they can be directly distinguished by Landsat images.	W: 100%

Удалено: 1…. Wetland types and fractional coverage of wetland ecosystems (Water …

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Удалено: ryams

Удалено: enriched by…ith close occurrence of groundwater. They flow and…frequently surround wetland systems; they can also be usually …ound in river valleys and, …young river …erraces and parts of the floodplains farthest from the river channels… They …

Удалено: are dominant in the WS taiga zone…onsists of alternating long narrow ridges and oligotrophic hollows. They purely depend on precipitation and the atmospheric input of nutrients. The configuration of ridges and hollows depend on the slope angle and hydrological conditions of the contiguous areas. RHCs with small, medium, and large hollows are usually …

Удалено: from RHCs or …atterned fens…etlands under permanent water stagnation or after seasonal flooding… RHLCs are the most abundant in northern taigas and occupy poorly drained watersheds… They may include the presence of …umerous prolate shallow pools. The class incorporates two types:…ollows can be both 1) with…oligotrophic, 2) …and with …eso- or eutrophic hollows …

Удалено: WS …WSL type of aapa mires. Patterned fens are composed of meso- or eutrophic open fen hollowsenvironments…that …lternatinge…with narrow ridges. Their…vegetation cover commonly includes sedge-moss or sedge …

Удалено: Patterned fens with small, medium, and large hollows can be arranged within the class.

Удалено: with heights …f 0.5-1 heightm that contain permafrost… They appear …

Удалено: along …t the periphery of wetland systems. They and…are characterized by presence ofmosaic…dwarf shrubs-sphagnum vegetation cover with sparse dwarf pine …

Удалено: WS …WSL taigas… They are confined to locations…ccupy areas with higher mineral supplies along …t the periphery of large peatland …etland systems or…and …long peatland …atercourses and areas with rich ground water supplies… The vegetation cover of open fens …

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Table 3. Latitudinal distribution of wetland ecosystem types

Wetland ecosystem types	South taiga		Middle taiga		North taiga		*Total area*	
	Area, Mha	%	Area, Mha	%	Area, Mha	%	*Area, Mha*	*%*
Open water	0.37	3	1.66	9	3.91	19	*5.94*	*11.3*
Waterlogged hollows	0.50	4	1.32	7	3.40	16	*5.22*	*10.0*
Oligotrophic hollows	1.87	16	5.78	30	5.60	27	*13.25*	*25.3*
Ridges	1.70	14	3.61	19	3.37	16	*8.69*	*16.6*
Ryams	3.37	28	5.14	27	1.60	8	*10.11*	*19.3*
Fens	4.22	35	1.77	9	1.53	7	*7.52*	*14.3*
Palsa hillocks	0.00	0	0.00	0	1.71	8	*1.71*	*3.3*
Total wetland area	*12.04*		*19.27*		*21.13*		*52.44*	
Total zonal area	*42.96*		*56.56*		*58.46*		*157.97*	
Paludification, %	*28.0*		*34.1*		*36.1*		*33.2*	

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Table 4. Confusion matrix of West Siberian wetland map validation (additional 11 floodplain and 33 mixed class polygons classified as wetlands are not presented)

Real classes / Estimated classes	Non-wetland	Lakes and rivers	RHLC	Pine bogs	RHC	Open Fens	Patterned Fens	Swamps	Palsa complexes	Open bogs	*Total*	*UA[1], %*
Non-wetland	**110**			1						2	*113*	*97*
Lakes and rivers		**94**	3					1			*98*	*96*
RHLC	4	7	**69**	1	4				2		*87*	*79*
Pine bogs	3		1	**108**	7		4			7	*130*	*83*
RHC	1		6	2	**150**	5	9			8	*181*	*83*
Open Fens			3	1	3	**86**	20			3	*116*	*74*
Patterned Fens	1		4	1		18	**68**				*92*	*74*
Swamps	5					4	9	**82**			*100*	*82*
Palsa complexes	13		1	2	1				**54**	3	*74*	*73*
Open bogs				1	7	1				**38**	*47*	*81*
Total	*137*	*101*	*87*	*117*	*172*	*114*	*110*	*83*	*56*	*61*	**1038**	
PA[2], %	*80*	*93*	*79*	*92*	*87*	*75*	*62*	*99*	*96*	*62*		

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Удалено: Ryams

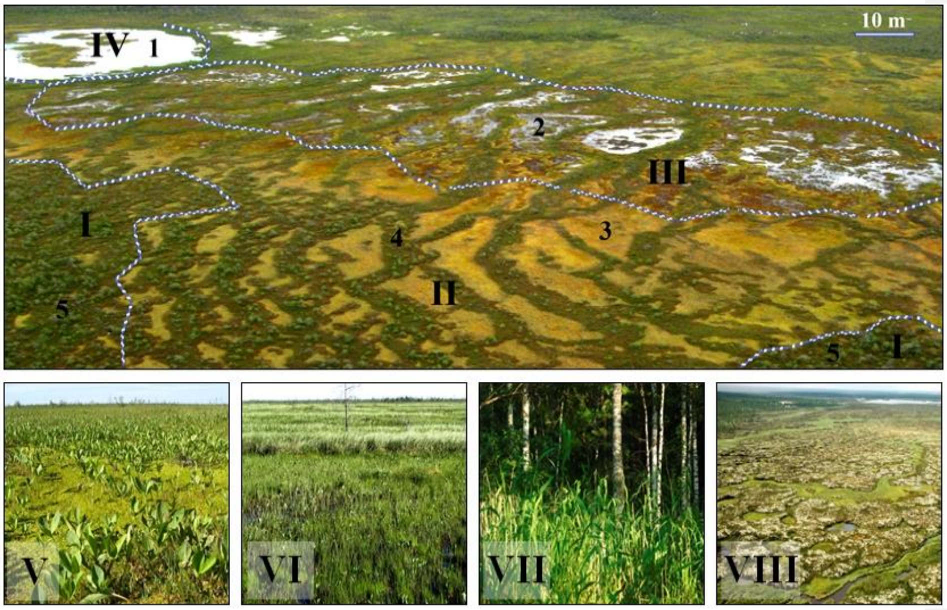

Figure 1. Wetland complexes (I – Pine bog or ryam, II – Ridge-hollow complex or RHC, III – Ridge-hollow-lake complex or RHLC, IV – Lakes and rivers, V – Open fens, VI – Patterned fens, VII – Swamps, VIII – Palsa complexes) and ecosystems in WSL (1 – Open water, 2 – Waterlogged hollows, 3 – Oligotrophic hollows, 4 – Ridges, 5 – Ryam)

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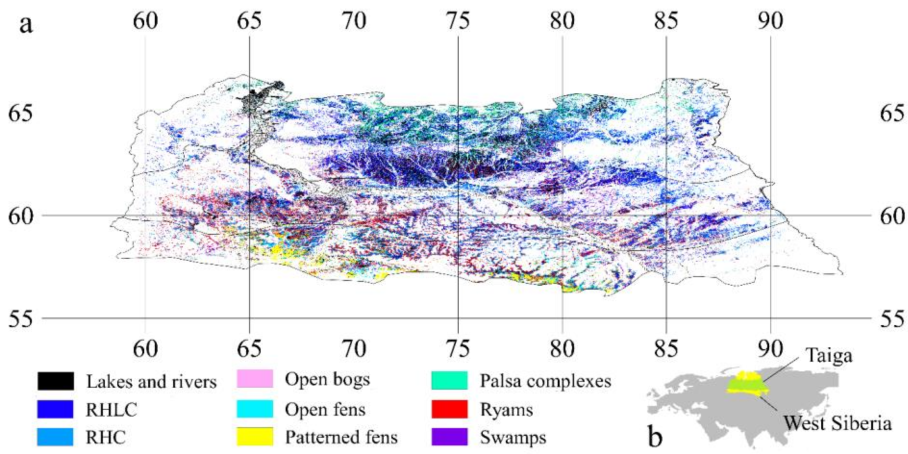

Figure 2. Wetland map (a) of the WSL taiga zone (b; yellow – WS, green – taiga zone)

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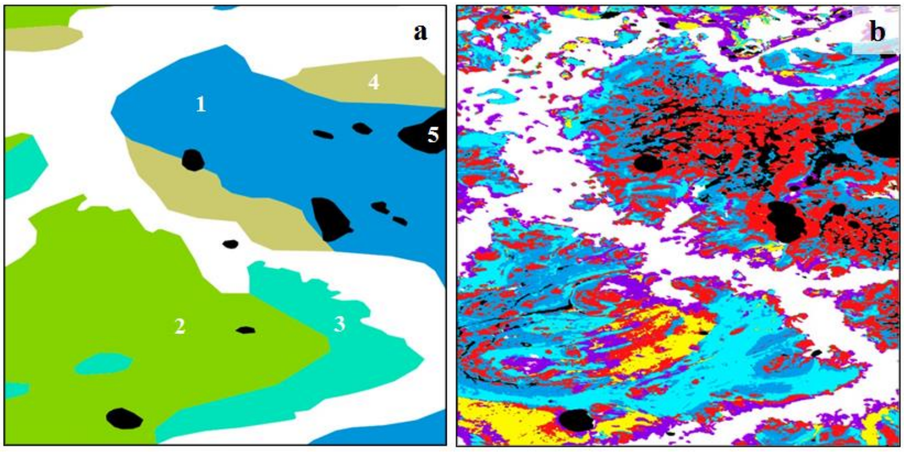

Figure 3. Comparison of wetland classifications: a – SHI map (1 – Sphagnum-dominated bogs with pools and open stand of trees, 2 – ridge-hollow, ridge-hollow-pool and ridge-pool patterned bogs, 3 – forested shrubs- and moss-dominated mires, 4 – moss-dominated treed mires, 5 – water bodies), b – this study (legend is on Figure 2); 59-59.5°N, 66-66.5°E

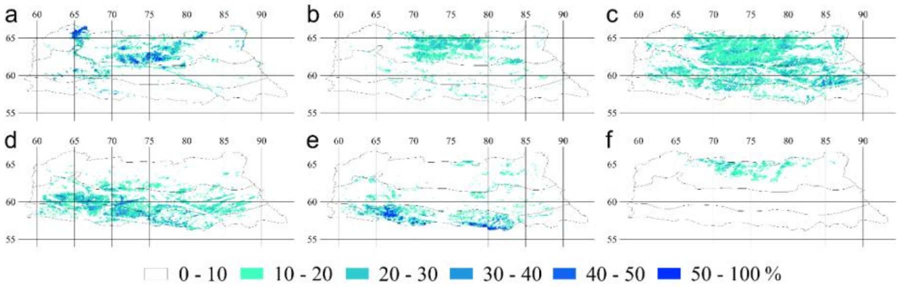

Figure 4. Wetland ecosystem areas for 0.1°×0.1° (% from the total cell area): a – open water, b – waterlogged hollows, c – oligotrophic hollows, d – ryams, e – fens, f – palsa hillocks; the distribution of ridges is not represented because it is quite similar to the oligotrophic hollow distribution; the black outlines divide the taiga into the north, middle and south taiga subzones

Mapping of West Siberian taiga wetland complexes using Landsat imagery: Implications for methane emissions

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Abstract

High latitude wetlands are important for understanding climate change risks because these environments sink carbon dioxide and emit methane. Fine-scale heterogeneity of wetland landscapes poses a serious challenge when generating regional-scale estimates of greenhouse gas fluxes from point observations. To reduce uncertainties at the regional scale, we mapped wetlands and water bodies in the taiga zone of The West Siberia Lowland (WSL) on a scene-by-scene basis using a supervised classification of Landsat imagery. Training data consists of high-resolution images and extensive field data collected at 28 test areas. The classification scheme aims at supporting methane inventory applications and includes 7 wetland ecosystem types comprising 9 wetland complexes distinguishable at the Landsat resolution. To merge typologies, mean relative areas of wetland ecosystems within each wetland complex type were estimated using high-resolution images. Accuracy assessment based on 1082 validation polygons of 10×10 pixel size indicated an overall map accuracy of 79%. The total area of the WS wetlands and water bodies was estimated to be 52.4 Mha or 4-12% of the global wetland area. Ridge-hollow complexes prevail in WS's taiga zone accounting for 33% of the total wetland area, followed by pine bogs or "ryams" (23%), ridge-hollow-lake complexes (16%), open fens (8%), palsa complexes (7%), open bogs (5%), patterned fens (4%), and swamps (4%).

Удалено: Fine scale heterogeneity of wetland landscapes pose challenges for producing the greenhouse gas flux inventories based on point observations

Удалено: recorded

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Удалено: The training dataset was based on high-resolution images and field data that were collected at 28 test areas

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Удалено: Classification scheme was aimed at methane inventory applications and included 7 wetland ecosystem types composing 9 wetland complexes in different proportions

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Various oligotrophic environments are dominant among wetland ecosystems, while poor fens cover only 14% of the area. Because of the significant change in the wetland ecosystem coverage in comparison to previous studies, a considerable reevaluation of the total CH_4 emissions from the entire region is expected. A new Landsat-based map of WS's taiga wetlands provides a benchmark for validation of coarse-resolution global land cover products and wetland datasets in high latitudes.

1 Introduction

High latitude wetlands are important for understanding climate change mechanism as they provide long term storage of carbon and emit significant amount of methane. The West Siberia Lowland (WSL) is the world's largest high-latitude wetland system and experiences an accelerated rate of climate change (Solomon et al., 2007).

Poorly constrained estimates of wetland and lake area constitute a major uncertainty in estimating current and future greenhouse gas emissions (Melton et al., 2013; Turetsky et al., 2014; Petrescu et al., 2010). Although wetland extent in WSL has been reasonably well captured by global products based on topographic maps (Lehner and Döll, 2004; Matthews and Fung, 1987), fine-scale heterogeneity of WSL's wetland landscapes (Bohn et al., 2007) requires adding fine scale information in ecosystem functioning as made in wetland CH_4 emission inventory (Glagolev et al., 2011) and estimates of net primary production (Peregon et al., 2008). Present land cover products fail to capture fine-scale spatial variability within WSL's wetlands because of lack of detail necessary for reliable productivity and emissions estimates. Frey and Smith (2007) mentioned insufficient accuracy of four global vegetation and wetland products with the best agreement of only 56% with the high-resolution WSL Peatland Database (WSLPD) (Sheng et al., 2004). Some products (Schroeder et al., 2010; Papa et al., 2010) tend to map only inundation, overlooking areas of «unsaturated» wetlands where the water table is below the moss cover. Because boreal peatlands does not experience prolonged inundation, such products underestimate their area (Krankina et al., 2008). Uncertainty in wetland inventory results in severe biases in CH_4 emission estimates, the scale of differences has been shown by Bohn et al. (2015).

Modelers simulating methane emission are in need for high-resolution wetland maps that do not only delineate wetlands but also identify the major sub-types to which different environmental parameters could potentially be applied (Bohn et al., 2015). Several wetland

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Удалено: West Siberia (WS) is the world's largest high-latitude wetland system situating in the high latitudes experiencing accelerated rate of climate change

Удалено: It was found both at global and regional scales that poorly constrained estimates of wetland and lake area is a major uncertainty in predicting current and future of greenhouse gas budget

Удалено: (Matthews and Fung, 1987; Lehner and Doll, 2004)

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Удалено: on fine scale heterogeneity

Удалено: Fine-scale heterogeneity of WSL's wetland landscapes Fine scale heterogeneity of WS wetland landscapes (Bohn et al., 2007; Eppinga et al., 2010; Bridgham et al., 2013) is not accurately accounted for when wetland CH_4 emission inventories pose challenges for producing inventories of methane emissions (Glagolev et al., 2011) and wetland net primary production (Peregon et al., 2008) are generated from point-scale field observationswhich are based on large number of point scale field measurements.. ¶

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maps have been used to define the wetland extent in WSL, however their application to net primary production (NPP) and methane emission inventories was accompanied by difficulties due to crude classification scheme, limited ground truth data and low spatial resolution. One peatland typology map that distinguishes several vegetation and microtopography classes and their mixtures was developed at the State Hydrological Institute (SHI) by Romanova et al. (1977). Peregon et al. (2005) digitized and complemented this map by estimating the fractional coverage of wetland structural components using Landsat images and aerial photographs for five test sites. However, the limited amount of fractional coverage data and coarse resolution still result in large uncertainties in upscaling methane fluxes (Kleptsova et al., 2012).

Our goal was to develop a multi-scale approach for mapping wetlands using Landsat imagery with a resolution of 30 m so the results could better meet the needs of land process modelling and other applications concerning methane emission from peatlands. In this study, the WSL taiga zone was chosen as the primary target for the land cover classification due to wetland abundance. The objectives were: first, to develop a consistent land cover of wetland classes and its structural components; second, to provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, net ecosystem exchange, biomass, etc) and validation of the process models.

2 Materials and Methods

2.1 Study Region

The West Siberian Lowland is a geographical region of Russia bordered by the Ural Mountains in the west and the Yenisey River in the east; the region covers 275 Mha within 62-89°E and 53-73°N. Because of its vast expanse and flat terrain, the vegetation cover of the Lowland shows clear latitudinal zonation. According to Gvozdetsky (1968), the taiga zone is divided into three geobotanical subzones: northern taiga, middle taiga and southern taiga. Taiga corresponds to the raised string bog province and covers about 160 Mha in the central part of the WS. It is characterized by flat terrain with elevations of 80 to 100 m above sea level rising to about 190 m in the «Siberian Uvaly» area. Average annual precipitation is about 450-500 mm and evaporation is 200-400 mm (National Atlas of Russia, 2008). The excess water supply and flat terrain with poor drainage provides favorable conditions for wetland formation. Comprehensive

Удалено: strong generalization of classes

Удалено: Various wetland maps have been used to define the wetland extent in WS, however simplistic classification schemes in aggregate to limited or no ground truth data and strong generalization of classes diminish their applicability

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Удалено: digitized and complemented this map by estimating the fractional coverage of wetland structural components or wetland ecosystems using Landsat and high-resolution images for five test sites.

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Удалено: Large fraction of the area, including watersheds and floodplains, is waterlogged. The hydrographic structure of this zone differs from the northern and southern parts of the WS. The largest peatlands are most typical of the central flat parts of the watersheds where, together with forests, they comprise the zonal vegetation and cover vast territories (Solomeshch, 2005).

synthesis of Russian literature regarding the current state of the WSL peatlands, their development and sensitivity to climatic changes was made by Kremenetski et al. (2003).

2.2 Classification methodology

No single classification algorithm can be considered as optimal methodology for improving vegetation mapping; hence, the use of advanced classifier algorithms must be based on their suitability for achieving certain objectives in specific applications (Adam et al., 2009). Because mapping over large areas typically involves many satellite scenes, multi-scene mosaicking is often used to group scenes into a single file set for further classification. This approach optimizes both the classification process and edge matching. However, large multi-scene mosaicking has essential drawback when applying to highly heterogeneous WSL wetlands. It creates a variety of spectral gradients within the file (Homer and Gallant, 2001), especially when the number of the appropriate scenes is limited. It results in spectral discrepancy that is difficult to overcome. In this study, the advantages of consistency in class definition of the scene-by-scene classification approach were considered to outweigh the inherent disadvantages of edge matching and processing labor. Thus, our entire analysis was performed on a scene-by-scene basis, similarly to efforts by Giri et al. (2011) and Gong et al. (2013).

For land cover consistency, data of the same year and season, preferably of the growing season peak (July) are required. However, the main complication was the low availability of good quality cloudless images of WSL during those periods. Scenes collected earlier than the 2000s were very few, so they were used as substitutes for places where no other suitable imagery could be found. Landsat-7 images received after 2003 were not used due to data gaps, while Landsat-8 was launched after the starting our mapping procedure. Finally, we collected 70 suitable scenes during the peak of the growing seasons in different years. Majority of the images were Landsat 5 TM scenes from July 2007. The scene selection procedure was facilitated by the ability of smoothing the slight inconsistencies between images by specifying training sites in overlapping areas.

The overall work flow involves data pre-processing, preparation of the training and test sample collections, image classification on a scene-by-scene basis, regrouping of the derived classes into 9 wetland complexes, the estimation of wetland ecosystem fractional coverage and accuracy assessment. Atmospheric correction was not applied because this process is unnecessary as long as the training data are derived from the image being classified (Song et

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Удалено: The study summarizes information about WS geology, hydrology, climate, vegetation, and peatland zonation. Basing on existing Russian data, authors found that the mean depth of peat accumulation in the WSL is 256 cm and the total amount of carbon stored there may exceed 54×10^{9} metric tons.

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Удалено: with same season with similar vegetation and hydrological conditions

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Удалено: The scene selection procedure was facilitated by the possibility of adequately smoothing the slight inconsistencies between images by specifying training sites in overlapping areas.

Удалено: wetland map continuity between adjacent scenes

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al., 2001). All of the images were re-projected onto the Albers projection. Because the WSL vegetation includes various types of forests, meadows, burned areas, agricultural fields, etc., wetland environments were first separated from other landscapes to avoid misclassification. We used thresholds of the Green-Red Vegetation Index (Motohka et al., 2010) to separate majority of wetlands and forests. Thresholds of the 5th Landsat channel (1.55-1.75 µm) was used to mask water bodies and many inundated areas (even vegetated) with the water level up to a few cm below the soil surface. Thresholds were empirically determined for each scene by testing various candidate values. Masked Landsat images were filtered in MATLAB v.7.13 (MathWorks) to remove random noise and then classified in Multispec v.3.3 (Purdue Research Foundation) using a supervised classification method. The maximum likelihood algorithm was used because of its robustness and availability in almost any image-processing software (Lu and Weng, 2007). All Landsat bands except the thermal infrared band were used.

Training data plays a critical role in the supervised classification technique. Representative data preparation is the most time-consuming and labour-intensive process in regional scale mapping efforts (Gong et al., 2013). As a primary source of information, we used the extensive dataset of botanical descriptions, photos, pH and electrical conductivity data from 28 test sites in WSL (Glagolev et al., 2011). Due to vast expanse and remoteness of WSL, we still had a lack of the ground truth information, which hampered training dataset construction. As a result, we had to rely mostly on high-resolution images available from Google Earth. They came from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics; multispectral images were reduced to visible bands (blue, green, red) and had spatial resolution of 1-3 meters. The processing started with mapping scenes where ground truth data and high-resolution images are extensively available, so the classification results could be checked for quality assurance; mapping continued through adjacent images and ended at the less explored scenes with poor ground truth data coverage.

To collect training data most efficiently, we used criteria similar to those used by (Gong et al., 2013) for training sample selection: (i) the training samples must be homogeneous; mixed land-cover and heterogeneous areas are avoided; and (ii) all of the samples must be at least 10 pixels in size with an average sample area of approximately 100-200 pixels. The Bhattacharyya distance was used as a class separability measure. The classifier was designed using training samples and then evaluated by classifying input data. The percentage of misclassified samples was taken as an optimistic predication of classification performance (Jain et al., 2000). When

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accuracy of more than 80% across the training set was attained with no fields showing unreasonable or unexplainable errors, the classification process was started. Classification mismatch between scenes was minimized by placing training samples in overlapping areas. Combining the classified images and area calculations were made using GRASS module in Quantum GIS. Noise filter was applied to eliminate objects smaller than 2×2 pixels. After that, a 10×10-pixel moving window was used to determine the dominant class, which was further assigned to the central 4×4-pixel area.

2.3 Wetland typology development

As a starting point for the mapping procedure, a proper classification scheme is required. Congalton et al. (2014) showed that the classification scheme alone may result in largest error contribution and thus deserves highest implementation priority. Its development should rely on the study purposes and the class separability of the input variables. In our case, wetland mapping was initially conceived as a technique to improve the estimate of the regional CH_4 emissions and, secondarily, as a base to upscale other ecological functions. WSL wetlands are highly heterogeneous, however, within each wetland complex we can detect relatively homogeneous structural elements or "wetland ecosystems" with similar water table levels (WTL), geochemical conditions, vegetation covers and, thus, rates of CH_4 emissions (Sabrekov et al., 2013). To ensure a reliable upscaling, we assigned 7 wetland ecosystems in our classification scheme (Fig. 1; Table 1).

However, wetland ecosystems generally have sizes from a few to hundreds of meters and cannot be directly distinguished using Landsat imagery with 30-meter resolutions. Therefore, we developed a second wetland typology that involves 9 mixed "wetland complexes" composing wetland ecosystems in different proportions (Fig. 1; Table 2). The classification were adapted from numerous national studies (Katz and Neishtadt, 1963; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompassed wooded, patterned, open wetlands and water bodies. The criteria for assigning wetland complexes were: (i) separability on Landsat images, and (ii) abundance in the WSL taiga zone. Each wetland complex represents integral class containing several subtypes differing in vegetation composition and structure. Subtypes were mapped using Landsat images and then generalized into final 9 wetland complexes basing upon ecosystem similarity and spectral separability.

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The spectral classes that were discriminated during the supervised classification were generalized into 9 wetland complexes.

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Удалено: Wetlands and water bodies that are only one or a few Landsat pixels in size exist, and some of these sites may be random image noises. Therefore, firstly we applied noise filter to eliminate objects smaller than 2×2 pixels. Then, a 10×10-pixel mobile window was used to determine the dominant class, which was further assigned to the central 4×4-pixel.

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To merge typologies, we estimated relative areas of wetland ecosystems within each wetland complex of the final map. Depending on heterogeneity, 8 to 27 test sites of 0.1-1 km^2 size were selected for each heterogeneous wetland complex. High-resolution images of 1-3 m resolution corresponding to these areas were classified in Multispec v.3.3 using visible channels. An unsupervised ISODATA classification was done on the images specifying 20 classes with a convergence of 95%. Obtained classes were manually reduced to seven wetland ecosystem types. Their relative proportions were calculated and then averaged among the test sites.

Thus, we used multiscale approach relying in two typologies. First, typology of wetland complexes was used for mapping Landsat images; second, typology of wetland ecosystems was used for upscaling CH_4 fluxes. The approach is similar to one devised by Peregon et al. (2005), where relative area proportions of “micro-landscape” elements within SHI wetland map were used for NPP data upscaling.

During wetland typology development, we made several assumptions. Firstly, the wetland complexes were considered as individual objects, while they actually occupy a continuum with no clustering into discrete units. Secondly, we assumed that all of the wetland water bodies originated during wetland development have sizes less than 2×2 Landsat pixels. They are represented by wetland pools and waterlogged hollows, which are structural components of RHLC. The rest of the water bodies were placed into the “Lakes and rivers” class. Thirdly, in this study, we only consider peatlands and water bodies; floodplain areas were separated from wetlands during the classification process.

The concept of wetland ecosystems has merits for CH_4 emission inventory. Methane emission depends mainly on water table level, temperature, and trophic state (Dise et al., 1993; Dunfield et al., 1993; Conrad, 1996). We take into consideration temperature, when we upscale fluxes separately for southern, middle and northern taiga. We take into consideration trophic state, when we map wetland complexes using multispectral Landsat images. We take into consideration water table level, when we map vegetation of wetland ecosystems with high-resolution images, because vegetation reflects soil moisture conditions. We do not directly consider smallest spatial elements as hummocks and tussocks. This omission introduces some uncertainty in regional CH_4 emission estimate, which was evaluated by (Sabrekov et al., 2014). Accordingly, reliable estimate of CH_4 fluxes accounting for fine spatial detail requires large number of measurements. Such heterogeneity is being addressed by measuring fluxes in all microforms in the field and then obtaining probability density distributions.

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“Waterlogged hollows”: water bodies fewer than 2×2 Landsat pixels or depressed parts of wetland complexes with WTLs above the average moss/vegetation surface;¶
“Oligotrophic hollows”: depressed parts of bogs with WTLs beneath the average moss/vegetation cover;¶
“Ridges”: long and narrow elevated parts of wetland complexes with dwarf shrubs-sphagnum vegetation cover;¶
“Ryams”: extensive pine-dwarf shrubs-sphagnum peatland areas;¶
“Fens”: integrated class for various types of rich fens, poor fens and wooded swamps;¶
“Palsa hillocks”: elevated parts of palsa complexes with permafrost below the surface.¶ ...
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3 Results and Discussion

3.1 Wetland map

Based on Landsat imagery, we developed a high-resolution wetland inventory of the WSL taiga zone (Fig. 2). The total area of wetlands and water bodies was estimated to be 52.4 Mha. West Siberian taiga wetlands are noticeable even from global prospective. The global total of inundated areas and peatlands was estimated to cover from 430 (Cogley, 1994) to 1170 Mha (Lehner and Döll, 2004) as summarized by Melton et al. (2013); therefore, taiga wetlands in WSL account for approximately from 4 to 12% of the global wetland area. Their area is larger than the wetland areas of 32.4, 32, and 41 Mha in China (Niu et al., 2012), Hudson Bay Lowland (Cowell, 1982) and Alaska (Whitcomb et al., 2009), respectively. The extent of West Siberia's wetlands exceeds the tropical wetland area of 43.9 Mha (Page et al., 2011) emphasizing the considerable ecological role of the studied region.

As summarized by Sheng et al. (2004), the majority of earlier Russian studies estimated the extent of the entire WS's mires to be considerably lower. These studies probably inherited the drawbacks of the original Russian Federation Geological Survey database, which was used as the basis for the existing WSL peatland inventories (Ivanova and Novikova, 1976). This database suffered from lack of field survey data in remote regions, a high generalization level and only considered economically valuable peatlands with peat layers deeper than 50 cm.

Our peatland coverage is similar to the estimate of 51.5 Mha (Peregon et al., 2009) by SHI map (Romanova et al., 1977). However, a direct comparison between the peatland maps shows that the SHI map is missing important details on the wetland distribution (Fig. 3). SHI map was based on aerial photography, which was not technically viable for full and continuous mapping of a whole region because it is too costly and time-consuming to process (Adam et al., 2009).

Distribution of wetland ecosystem areas have changed significantly in comparison to SHI map (Peregon et al., 2009); in particular, we obtained 105% increase in spatial extent of CH_4 high-emitting ecosystems such as waterlogged, oligotrophic hollows and fens. In the case study of WS's middle taiga, we found that applying the new wetland map led to a 130% increase in the CH_4 flux estimate from the domain (Kleptsova et al., 2012) in comparison with the estimate based on SHI map. Thus, a considerable revaluation of the total CH_4 emissions from the whole region is expected.

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Удалено: The satellite-based classifications tend to identify many small peatlands and their subgroups, which are ignored in the more generalized SHI map. However, the satellite classifications also delineate small gaps within contiguous peatlands. The net result of both effects is a fortuitous cancellation of their differences (Sheng et al., 2004), leaving the discrepancy in the spatial distributions. The latter is essential for environmental parameter upscaling purposes.
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3.2 Regularities of zonal distribution

WS has a large variety of wetlands that developed under different climatic and geomorphologic conditions. Concerning the wetland complex typology (excluding "Lakes and rivers" class), RHCs prevail in WS's taiga, accounting for 32.2% of the total wetland area, followed by pine bogs (23%), RHLCs (16.4%), open fens (8.4%), palsa complexes (7.6%), open bogs (4.8%), patterned fens (3.9%) and swamps (3.7%). Various bogs are dominant among the wetland ecosystems (Table 3), while fens cover only 14.3% of the wetlands. Waterlogged hollows and open water occupy 7% of the region, which is similar to the estimate by Watts et al. (2014), who found that 5% of the boreal-Arctic domain was inundated during summer season.

The individual wetland environments have a strongly pronounced latitudinal zonality within the studied region. Zonal borders stretch closely along latitude lines, subdividing the taiga domain into the southern, middle, and northern taiga subzones (Fig. 2, black lines). To visualize the regularities of the wetland distribution, we divided the entire area into 0.1°×0.1° grids and calculated ratios of wetland ecosystem areas to the total cell areas for each grid (Fig. 4) using fractional coverage data from Table 2.

Mire coverage of WSL's northern taiga (62-65°N) is approximately 36%. Because of the abundance of precipitation, low evaporation and slow runoff, the northern taiga is characterized by largest relative area of lakes and waterlogged hollows, covering a third of the domain (Fig. 4a, b). Vast parts of the zone are occupied by the peatland system "Surgutskoe Polesye," which stretches for one hundred kilometers from east to west between 61.5°N and 63°N. Peatland and water bodies cover up to 70% of the territory, forming several huge peatland-lake complexes divided by river valleys. Northward, the slightly paludified "Sibirskie Uvaly" elevation (63.5°N) divides the northern taiga into two lowland parts. Palsa hillocks appear in the "Surgutskoe Polesye" region and replace the ridges and ryams to the north of the "Sibirskie Uvaly" region (Fig. 4f).

RHCs are the most abundant in the middle taiga (59-62°N), where mires occupy 34% of the area. Large wetland systems commonly cover watersheds and have a convex dome with centres of 3-6 m higher than periphery. These environments have peat layer of several meters depth composed of sphagnum peat with the small addition of other plants. The wetland ecosystems here have distinct spatial regularities. Central plateau depressions with stagnant water are covered by RHLCs. Different types of RHCs cover better-drained gentle slopes. The most

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drained areas are dominated by ryams. Poor and rich fens develop along wetland's edges with relatively high nutrient availability. Wooded swamps usually surround vast wetland systems.

The wetland extent reaches 28% in WS's southern taiga area (56-59°N). Wetlands are composed of raised bogs alternating with huge open and patterned fens. The eastern part of the subzone is dominated by small and medium-sized wetland complexes. The southern and middle taiga wetlands exhibit similar spatial patterns; however, the area of fens increases southwards due to the abundance of carbonate soils and higher nutrient availability. Velichko et al. (2011) provide evidence for existence of a vast cold desert in the northern half of the WSL at the late glacial time, whereas the southernmost part was an area of loess accumulation. The border between fen and bog-dominated areas extends near 59°N and corresponds to the border between the southern and middle taiga zones (Fig. 4c and e).

3.3 Accuracy assessment

The map accuracy assessment was based on 1082 validation polygons of 10×10 pixels that were randomly spread over the WSL taiga zone. We used high-resolution images available in Google Earth as the ground truth information. The confusion matrix (Table 4) was used as a way to represent map accuracy (Congalton and Green, 2008). Overall, we achieved the classification accuracy of 79% that can be considered reasonable for such a large and remote area. We found that the accuracies for different land-cover categories varied from 62 to 99%, with the lake and river, ryam, and RHC class areas mapped most successfully and open bogs and patterned fens being the most confused. Some errors were associated with mixed pixels (33 polygons), whose presence had been recognized by Foody (2002) as a major problem, affecting the effective use of remotely sensed data in per-pixel classification.

Wetland complexes within large wetland systems had the highest classification accuracies. In contrast, the uncertainties are particularly high for small objects. It is of special importance in southern part of the domain, where highly heterogeneous agricultural landscapes neighbour upon numerous individual wetlands of 100-1000 ha area. Several vegetation indices was tested to map them; however, the best thresholding result was achieved by using Landsat thermal band. In addition, many errors happened along the tundra boundary, caused by the lack of ground truth data combined with the high landscape heterogeneity. However, those small areas mainly correspond to palsa complexes and have slight impact on CH_4 flux estimate.

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Удалено: The southern taiga wetlands have similar spatial regularities as the middle taiga; however, the area of the fens increases stepwise here due to the abundance of carbonate soils and the higher nutrient availability
Удалено: Velichko et al. (2011) provided evidence of a vast cold desert in the northern half of WS during the last glacial period, while the southernmost part of the plain was an area of loess accumulation. Now, the border between fen and bog dominated areas extends near 59°N and corresponds to the border between the southern and middle taiga zones (Fig. 4c, e).
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Misclassifications usually occurred between similar classes introducing only a minor distortion in map applications. Patterned fens and open bogs were classified with the lowest producer's accuracy (PA) of 62%. Patterned fens include substantial treeless areas, so they were often misclassified as open fens. They were also confused with RHCs due to the similar "ridge-hollow" structure. Some open bogs have tussock shrub cover with sparsely distributed pine trees provoking misclassification as RHCs and pine bogs. Open fens have higher user's accuracy (UA) and PA; however, visible channels of high-resolution images poorly reflect trophic state, which underrates classification errors between open bogs and open fens. Swamps and palsa complexes have very high PA and low UA, which is related to their incorrect identification in non-wetland areas. Palsa complexes were spectrally close to open woodlands with lichen layer, which covers wide areas of WSL north taiga. During dry period, swamps were often confused with forests, whereas in the field they can be easily identified through the presence of peat layers and a characteristic microrelief. In both cases, more accurate wetland masks would lead to substantially higher accuracy levels. Lakes and rivers were classified the best due to the high spectral separability of the class. They can be confused with RHLCs represented by a series of small lakes or waterlogged hollows alternating with narrow isthmuses. Floodplains after snow melt can also be classified as lakes (11 polygons). RHCs and pine bogs were accurately identified due to their abundance in the study region and high spectral separability.

3.4 Challenges and future prospects

The contrast between vast wetland systems and the surrounding forests is so distinct in WSL that wetlands can be adequately identified by the summer season images (Sheng et al., 2004). On the contrary, correct mapping of wetland with pronounced seasonal variations remains one of the largest challenges. Wetlands become the most inundated after snow melt or rainy periods resulting in partial transformation of oligotrophic hollows and fens into waterlogged hollows (see hollows with brown Sphagnum cover at Fig. 1). Image features of swamps after drought periods become similar to forests. Interannual variability of water table level in WSL wetlands (Schroeder et al., 2010; Watts et al., 2014) also makes impact on mapping results.

New methodologies and protocols are needed to improve our ability to monitor water levels (Kim et al., 2009). Observations of soil moisture and wetland dynamic using radar data such as PALSAR (Chapman et al., 2015; Clewley et al., 2015) and Global Navigation Satellite Signals Reflectometry are promising (Chew et al., 2016; Zuffada et al., 2015). Advanced classification

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techniques such as fuzzy logic can be applied for mapping fine-scale heterogeneity (Adam et al., 2009). Recent innovations in wetland mapping were described by Tiner et al. (2015).

Water table fluctuations are especially important for upscaling CH_4 fluxes because the spatial distribution of methane emissions, and therefore, the total methane emission, are functions of the spatial distribution of water table depths (Bohn et al., 2007). Wetland ecosystems with water levels close to surface contribute most to the regional flux, while the contribution of dryer ecosystems (ryams, ridges and palsa hillocks) is close to negligible (Glagolev et al., 2011; Sabrekov et al., 2014). _ENREF_59

Although the synergistic combination of active and passive microwave sensor data is advantageous for accurately characterizing open water (Schroeder et al., 2010) and wetlands, the remote sensing of water regimes is successful only when in situ data are available for calibration. We still lack in situ measurements of the water table dynamics within WSL wetlands. Limited monitoring have been made at the Bakchar field station (Krasnov et al., 2013; Krasnov et al., 2015) and Mukhrino field station (Bleuten and Filippov, 2008); however, the vast majority of obtained data are not yet analyzed and published. These measurements are of special importance for the northern taiga and tundra, where shallow thermokarst lakes with fluctuating water regimes cover huge areas.

The scarcity of reliable reference data and subsequent lack of consistency also limit the accuracy of maps (Homer and Gallant, 2001). The use of ancillary data can largely improve it (Congalton et al., 2014); however, more reliable classification accuracy comes with significant costs regarding detailed field data. The next step in map improvement should rely on the acquisition of more ground truth data for the poorly classified wetland types and remote regions.

4 Conclusions

Boreal peatlands play a major role in carbon storage, methane emissions, water cycling and other global environmental processes, but better understanding of this role is constrained by the inconsistent representation of peatlands on (or even complete omission from) many global land cover maps (Krankina et al., 2008). In this study, we developed a map representing the state of the taiga wetlands in WSL during the peak of the growing season. The efforts reported here can be considered as an initial attempt at mapping boreal wetlands using Landsat imagery, with the general goal of supporting the monitoring of wetland resources and upscaling the methane

- **Удалено:** The use of additional radar data to map the most inundated areas will be especially useful for CH_4 flux upscaling because
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- **Удалено:** most ambiguous
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- **Удалено:** Advanced classification techniques as fuzzy logic, which is a kind of probability-based classification rather than a crisp classification, are promising for solving the problem of mixed pixels when mapping complex vegetation (Adam et al., 2009).
- **Удалено:** describe
- **Удалено:** WS
- **Удалено:** Although _ENREF_17 highlighted that “per scene, interactive analyses will no longer be viable” for global land cover studies; however, we still find that the procedure is quite suitable for regional mapping with highly heterogeneous landscapes and low availability of good quality cloudless images.
- **Удалено:** Russian

emissions from wetlands and inland waters. The resulting quantitative definitions of wetland complexes combined with a new wetland map can be used for the estimation and spatial extrapolation of many ecosystem functions from site-level observations to the regional scale. In the case study of WS's middle taiga, we found that applying the new wetland map led to a 130% increase in the CH_4 flux estimation from the domain (Kleptsova et al., 2012) comparing with estimation based on previously used SHI map. Thus, a considerable reevaluation of the total CH_4 emissions from the entire region is expected.

We estimate a map accuracy of 79% for this large and remote area. The next step in improving mapping quality will depend on the acquisition of ground truth data from the least discernible wetland landscapes and remote regions. Correctly distinguishing wetland complexes with strongly pronounced seasonal variability in their water regimes remains one of the largest challenges. This difficulty can be resolved by installing water level gauge network and usage both combined remote sensing data and advanced classification techniques.

Our new Landsat-based map of WS's taiga wetlands can be used as a benchmark dataset for validation of coarse-resolution global land cover products and for assessment of global model performance in high latitudes. Although classification scheme was directed towards improving CH_4 inventory, the resulting map can also be applied for upscaling of the other environmental parameters.

Acknowledgements

We thank Amber Soja and anonymous reviewers for assisting in improving the initial version of the manuscript. This study (research grant No 8.1.94.2015) was supported by The Tomsk State University Academic D.I. Mendeleev Fund Program in 2014-2015. The study was also supported by the GRENE-Arctic project by MEXT Japan.

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Удалено: In the case study of WS's taiga, applying a new wetland map led to a significant change in the wetland ecosystem areas comparing to the estimate by Peregon et al. (2009), previously used in our methane inventory (Glagolev et al., 2011).

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Table 1. Wetland ecosystem types

Wetland ecosystem	**Short description**	**WTL, cm (1st/2nd/3rd quartiles)[1]**
Open water	All water bodies greater than 2×2 Landsat pixels	-
Waterlogged hollows	Open water bodies fewer than 2×2 Landsat pixels or depressed parts of wetland complexes with WTLs above the average moss/vegetation surface	-10 / -7 / -4
Oligotrophic hollows	Depressed parts of bogs with WTLs beneath the average moss/vegetation cover	3 / 5 / 10
Ridges	Long and narrow elevated parts of wetland complexes with dwarf shrubs-sphagnum vegetation cover	20 / 32 / 45
Ryams	Extensive pine-dwarf shrubs-sphagnum areas	23 / 38 / 45
Fens	Integrated class for various types of rich fens, poor fens and wooded swamps	7 / 10 / 20
Palsa hillocks	Elevated parts of palsa complexes with permafrost below the surface	Less than 45

[1] Positive WTL means that water is below average moss/soil surface; the data was taken from field dataset (Glagolev et al., 2011)

Удалено: peatland

Table 2. Wetland types and fractional coverage of wetland ecosystems (Open water – W, Waterlogged hollows – WH, Oligotrophic hollows – OH, Ridges – R, Ryams – Ry, Fens – F, Palsa hillocks – P)

Wetland complexes	Short description	Wetland ecosystems
	Wooded wetlands	
Pine-dwarf shrubs-sphagnum bogs (pine bogs, ryams)	Dwarf shrubs-sphagnum communities with pine trees (local name – “ryams”) occupy the most drained parts of wetlands. Pine height and crown density are positively correlated with the slope angle. Ryams purely depend on precipitation and the atmospheric input of nutrients. The next evolutionary type under increased precipitation is RHC.	Ry: 100%
Wooded swamps	Wooded swamps develop in areas with close occurrence of groundwater. They frequently surround wetland systems; they can also be found in river valleys and terraces. Wooded swamps are extremely diverse in floristic composition and have prominent microtopography.	F: 100%
	Patterned wetlands	
Ridge-hollow complexes (RHC)	RHC consists of alternating long narrow ridges and oligotrophic hollows. They purely depend on precipitation and the atmospheric input of nutrients. The configuration of ridges and hollows depend on the slope angle and hydrological conditions of the contiguous areas. RHCs with small, medium, and large hollows can be arranged within the class.	R: 42% OH: 58%
Ridge-hollow-lake complexes (RHLC)	RHLCs develop on poorly drained watersheds or after seasonal flooding of patterned wetlands. RHLCs are the most abundant in northern taiga. They may include numerous shallow pools. Hollows can be both oligotrophic and meso- or eutrophic.	R: 31% OH: 25% WH: 31% F: 13%
Patterned fens	Patterned fens are widely distributed within the region. They correspond to the WSL type of aapa mires. Patterned fens are composed of meso- or eutrophic hollows alternating with narrow ridges. The vegetation cover commonly includes sedge-moss communities.	R: 28% F: 72%
Palsa complexes	Palsa complexes are patterned bogs with the presence of palsa hillocks – frost heaves of 0.5-1 height. They arise in the north taiga and prevail northwards. They may include numerous shallow pools.	WH: 12% OH: 37% P: 51%
	Open wetlands	
Open bogs	Open bogs are widespread at the periphery of wetland systems. They are characterized by presence of dwarf shrubs-sphagnum hummocks up to 30 cm in height and 50-200 cm in size.	OH: 100%
Open fens	Open fens are the integral class that encompasses all varieties of open rich and poor fens in WSL taiga. They occupy areas with higher mineral supplies at the periphery of wetland systems and along watercourses. The vegetation cover is highly productive and includes sedges, herbs, hypnum and brown mosses.	F: 100%
	Water bodies	
Lakes and rivers	All water bodies larger than 60×60 m², so they can be directly distinguished by Landsat images.	W: 100%

Удалено: 1…. Wetland types and fractional coverage of wetland ecosystems (Water

Удалено: the …etlands. The p…ine height and crown density are positively correlated with the slope angle. . The peat surface is usually approximately several decimeters high above the WTL. Ryams are typical oligotrophic mires that…yams purely depend on precipitation and the atmospheric input of nutrients. The ir …ext evolutionary type under increased precipitation or weaker drainage

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Удалено: enriched by…ith close occurrence of groundwater. They flow and…frequently surround wetland systems; they can also be usually …ound in river valleys and, …young river …erraces and parts of the floodplains farthest from the river channels… They

Удалено: are dominant in the WS taiga zone…onsists of alternating long narrow ridges and oligotrophic hollows. They purely depend on precipitation and the atmospheric input of nutrients. The configuration of ridges and hollows depend on the slope angle and hydrological conditions of the contiguous areas. RHCs with small, medium, and large hollows are usually

Удалено: from RHCs or …atterned fens…etlands under permanent water stagnation or after seasonal flooding… RHLCs are the most abundant in northern taigas and occupy poorly drained watersheds… They may include the presence of …umerous prolate shallow pools. The class incorporates two types:…ollows can be both 1) with…oligotrophic, 2) …and with …eso- or eutrophic hollows

Удалено: WS …WSL type of aapa mires. Patterned fens are composed of meso- or eutrophic open fen hollowsenvironments…that …lternatinge…with narrow ridges. Their…vegetation cover commonly includes sedge-moss or sedge

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Удалено: along …t the periphery of wetland systems. They and…are characterized by presence ofmosaic…dwarf shrubs-sphagnum vegetation cover with sparse dwarf pine

Удалено: WS …WSL taigas… They are confined to locations…ccupy areas with higher mineral supplies along …t the periphery of large peatland …etland systems or…and …long peatland …atercourses and areas with rich ground water supplies… The vegetation cover of open fens

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Table 3. Latitudinal distribution of wetland ecosystem types

Wetland ecosystem types	South taiga		Middle taiga		North taiga		*Total area*	
	Area, Mha	%	Area, Mha	%	Area, Mha	%	*Area, Mha*	*%*
Open water	0.37	3	1.66	9	3.91	19	*5.94*	*11.3*
Waterlogged hollows	0.50	4	1.32	7	3.40	16	*5.22*	*10.0*
Oligotrophic hollows	1.87	16	5.78	30	5.60	27	*13.25*	*25.3*
Ridges	1.70	14	3.61	19	3.37	16	*8.69*	*16.6*
Ryams	3.37	28	5.14	27	1.60	8	*10.11*	*19.3*
Fens	4.22	35	1.77	9	1.53	7	*7.52*	*14.3*
Palsa hillocks	0.00	0	0.00	0	1.71	8	*1.71*	*3.3*
Total wetland area	*12.04*		*19.27*		*21.13*		*52.44*	
Total zonal area	*42.96*		*56.56*		*58.46*		*157.97*	
Paludification, %	*28.0*		*34.1*		*36.1*		*33.2*	

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Table 4. Confusion matrix of West Siberian wetland map validation (additional 11 floodplain and 33 mixed class polygons classified as wetlands are not presented)

Real classes / Estimated classes	Non-wetland	Lakes and rivers	RHLC	Pine bogs	RHC	Open Fens	Patterned Fens	Swamps	Palsa complexes	Open bogs	*Total*	*UA*[1], *%*
Non-wetland	**110**			1						2	*113*	*97*
Lakes and rivers		**94**	3					1			*98*	*96*
RHLC	4	7	**69**	1	4				2		*87*	*79*
Pine bogs	3		1	**108**	7		4			7	*130*	*83*
RHC	1		6	2	**150**	5	9			8	*181*	*83*
Open Fens			3	1	3	**86**	20			3	*116*	*74*
Patterned Fens	1		4	1		18	**68**				*92*	*74*
Swamps	5					4	9	**82**			*100*	*82*
Palsa complexes	13		1	2	1				**54**	3	*74*	*73*
Open bogs				1	7	1				**38**	*47*	*81*
Total	*137*	*101*	*87*	*117*	*172*	*114*	*110*	*83*	*56*	*61*	**1038**	
PA[2]*, %*	*80*	*93*	*79*	*92*	*87*	*75*	*62*	*99*	*96*	*62*		

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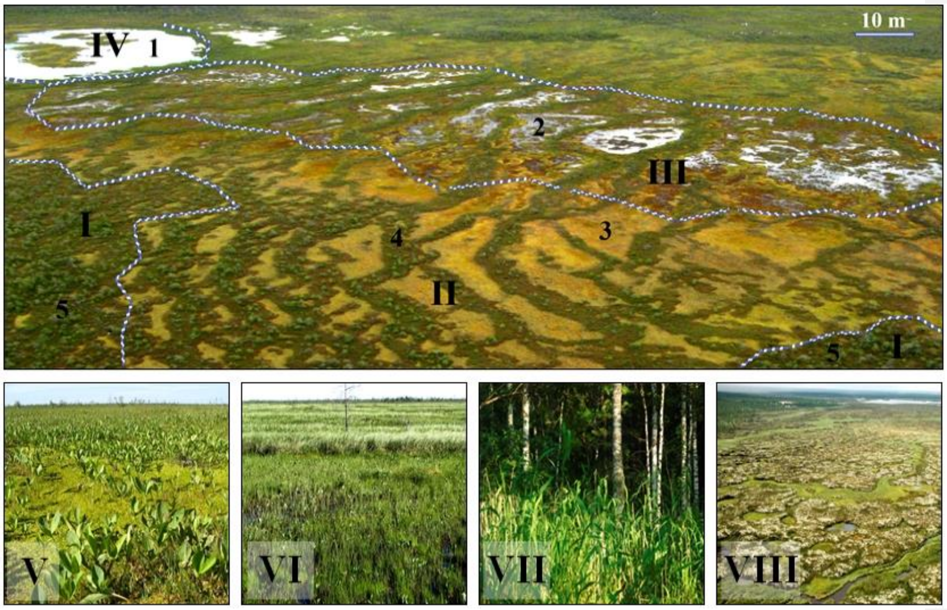

Figure 1. Wetland complexes (I – Pine bog or ryam, II – Ridge-hollow complex or RHC, III – Ridge-hollow-lake complex or RHLC, IV – Lakes and rivers, V – Open fens, VI – Patterned fens, VII – Swamps, VIII – Palsa complexes) and ecosystems in WSL (1 – Open water, 2 – Waterlogged hollows, 3 – Oligotrophic hollows, 4 – Ridges, 5 – Ryam)

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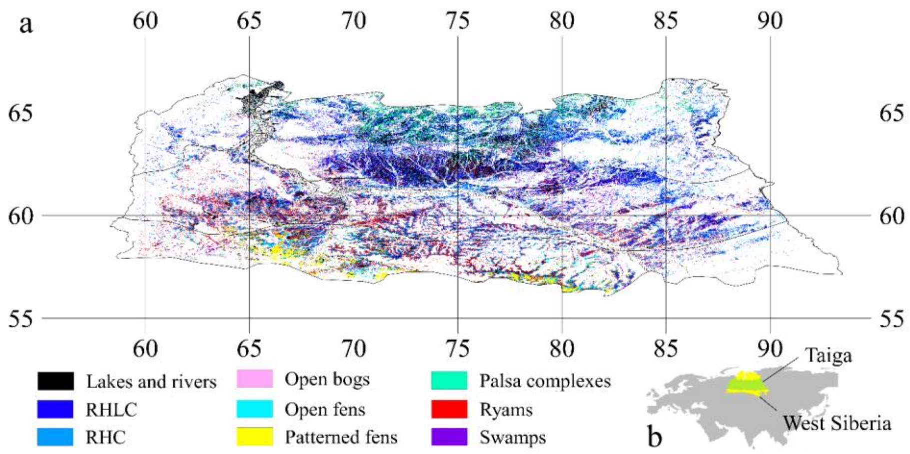

Figure 2. Wetland map (a) of the WSL taiga zone (b; yellow – WS, green – taiga zone)

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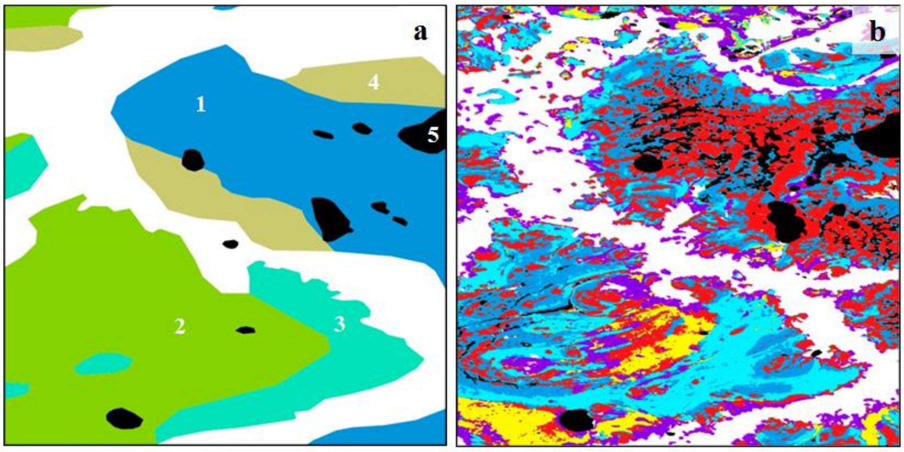

Figure 3. Comparison of wetland classifications: a – SHI map (1 – Sphagnum-dominated bogs with pools and open stand of trees, 2 – ridge-hollow, ridge-hollow-pool and ridge-pool patterned bogs, 3 – forested shrubs- and moss-dominated mires, 4 – moss-dominated treed mires, 5 – water bodies), b – this study (legend is on Figure 2); 59-59.5°N, 66-66.5°E

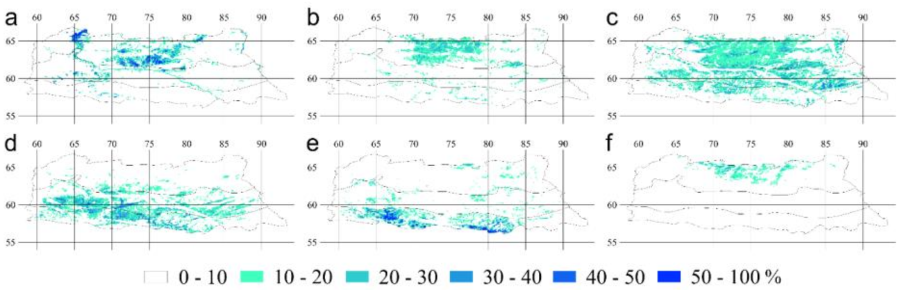

Figure 4. Wetland ecosystem areas for 0.1°×0.1° (% from the total cell area): a – open water, b – waterlogged hollows, c – oligotrophic hollows, d – ryams, e – fens, f – palsa hillocks; the distribution of ridges is not represented because it is quite similar to the oligotrophic hollow distribution; the black outlines divide the taiga into the north, middle and south taiga subzones