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. We also attach revised version of the manuscript with

<u>Response to the first referee</u>

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.

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 thank you 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 the title to: «Wetland mapping of West Siberian taiga zone using Landsat imagery: Implications for methane emissions». We decided to mention Landsat because it answers the question about the map resolution. We decided to mention taiga because it is two times smaller than whole 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 field 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.

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.

Revised:

«Present land cover products fail to capture fine-scale spatial variability within WSL’s wetlands because mixed pixels greatly decrease the accuracy of these products. 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, surface water 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!

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.

Revised: «…and third, to provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, NEE, biomass, etc) and the model adequacy assessment.»

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 NPP and methane emission inventories was accompanied by difficulties due to simplistic classification scheme, limited ground truth data and strong generalization of classes.»

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

We apologize for mistake. Revised version:

«Peregon et al. (2005) digitized and complemented this map by estimating the fractional coverage of wetland structural components or wetland ecosystems 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 introduce 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 favourable 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». Now we have shorten it.

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 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 suitable 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. 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 vegetation with low projective cover, when water or water-saturated soil can be seen through it. In general, grass vegetation become sparser with increasing inundation. Therefore, we usually can mask out such environments. In case of sphagnum mosses, areas with water up to a few cm below moss surface can be sensed using fifth Landsat band. Such areas were mentioned in the paper as «the most inundated». In case of dense tree layer, we actually cannot sense them using only 5th channel. To be more specific, we slightly changed the sentence:

«Thresholds of the 5th Landsat channel (1.55-1.75 µm) was used to mask water bodies and the most inundated areas (even with grass vegetation) 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 compliment training sample set by relying mostly on high-resolution images available on Google Earth. They come from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics. Multispectral images, which are reduced to visible bands (blue, green, red) and resolution of 1-3 meters, were used. There were limited or no meta-data available regarding image acquisition dates and spectral transformations.»

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

Changed to «The dataset was…».

23. L. 6 “contiguous”. Do you mean “adjacent”?

Revised.

24. 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, then continued through adjacent images and ended at the less explored scenes with poor ground truth data coverage.»

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

Histogram shapes of training data were analyzed (bi-modal/normal/too narrow or too wide) to visually judge the quality of training samples. Then we classified only training fields to verify their purity and separability using resubstitution errors (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 we started classification of the whole area.

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 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 future classification performance (Jain et al., 2000). When accuracy of more than 80% overall was attained with no fields showing unreasonable or unexplainable errors, the classification process was started.»

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

It was removed.

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

Revised: «Therefore, we applied noise filter 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.»

28. 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.

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

Revised: «To merge typologies, we estimated relative areas of wetland ecosystems within each of wetland complexes 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 corresponding to these areas were classified in Multispec v.3.3. An unsupervised ISODATA classification was done on the images specifying 20 classes with a 0.95 confidence interval. Obtained classes were manually reduced to seven wetland ecosystem types. Their relative proportions were calculated and then averaged among the test sites.»

30. 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 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.»

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

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 proved to be noticeable even at the global scale. 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.»

32. L. 25 "feasible" I believe that "reasonable", "practical" or "economical" may be better words here. Feasible simply means it's possible.

Revised.

33. 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.

34. 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.

35. 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 many examples in the papers, so we moved this sentence to the beginning of the corresponding paragraph.

Revised: «Misclassifications usually occurred between neighbouring classes similar in environmental parameters, which introduce only a minor distortion in map applications. Patterned fens and open bogs were classified with the lowest producer's accuracy (PA), which was 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. Open bogs often have tussock shrub cover with sparse pines, increasing the frequency of misclassification as RHCs and ryams...»

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

Revised: «Wetland complexes within large wetland systems have highest classification accuracies. In contrast, the uncertainties are particularly high for the 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 produced by Landsat thermal band.»

37. 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 our 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.»

38. 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.

39. L. 17 "interannual variability" of what? L. 18 "reasonable" Do authors mean "important"?

«Interannual variability of water table level also occurs in WSL (Schroeder et al., 2010; Watts et al., 2014). Water table fluctuations are especially important for upscaling CH4 fluxes…»

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

Revised: «Perhaps the best opportunity in the next few years for routine measurements of inundated areas will result from PALSAR (Chapman et al., 2015; Clewley 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)»

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 features 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 CH4 flux estimation from the domain (Kleptsova et al., 2012) comparing with estimation based on previously used SHI map. Thus, a considerable revaluation of the total CH4 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.

<u>Response to the second referee</u>

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.

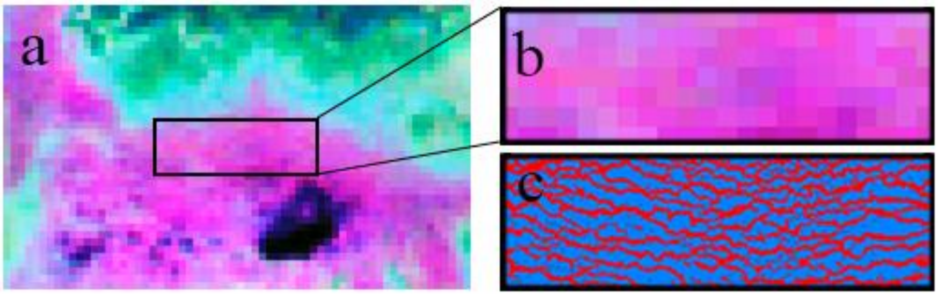
It was not clear from the abstract and introduction that actual application of the remote sensing data to wetland CH_4 emission inventory as done by Glagolev et al (2011) involves combining multiple scales of the geographical information. Previous analysis made by Peregon et al (2008, 2009) relied on 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 responce). 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. 1a,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. 1c from the response).

Fig. 1. 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 legend was developed specially for our goals (Fig. 3 from the paper). 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 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, current paper about the map and second 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.

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, 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 (see (Glagolev et al., 2011) and references there)

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 has the highest error contribution and 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 an advanced technique to improve the estimate of the regional CH_4 flux 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 yield reliable upscaling, we assigned 7 wetland ecosystems in our classification scheme (Fig. 1; Table 1).

However, wetland ecosystems generally have sizes of 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" (Fig. 1; Table 2). The assigned wetland complexes should meet the following criteria: (i) distinguishability by Landsat images, and (ii) abundance in the WSL taiga zone. All these complexes were described in detail in a number of Russian studies (Katz and Neishtadt, 1963; Walter, 1977; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompass wooded, patterned, open wetlands and water bodies.

To merge typologies, we estimated relative areas of wetland ecosystems within each of wetland complexes 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 corresponding to these areas were classified in Multispec v.3.3. An unsupervised ISODATA classification was done on the images specifying 20 classes with a 0.95 confidence interval. 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 to facilitate applying the resulting map to upscaling CH_4 fluxes. The approach is similar to described 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. First, the wetland complexes were considered as individual objects, while they usually occupy a continuum with no clustering into discrete units, so the boundaries between classes are based on assumptions. However, it has limited impact on methane inventory, because relative area proportions of wetland ecosystems can be estimated at the high resolution classification step for any given boundaries using images of 1-3 m resolution. Second, the classification schemes include all water bodies, although many (rivers, creeks, and large lakes) are not structural components of wetlands. Based on field knowledge, we assumed that all of the water bodies that arose from peatland development have sizes less than 2×2 Landsat pixels. These water bodies are represented by wetland pools, waterlogged hollows and watercourses, 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 conception of wetland ecosystems seems to be reasonable for CH_4 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 upscale measurements separately for southern, middle and northern taiga. We take into consideration water table level and trophic state, when we map vegetation cover using high-resolution images. However, we do not consider any spatial elements as hummocks and tussocks within wetland ecosystems. This approach introduces some uncertainty in regional methane emission estimate, which was evaluated by (Sabrekov et al., 2014). However, it is not possible to provide reliable estimates of methane fluxes on more detailed spatial scale due to number of measurements. On the contrary, accounting spatial variability at wetland ecosystem scale required about 100 flux measurements in each ecosystem type in every zone (Sabrekov et al., 2013)».

We have already changed title to «Wetland mapping of West Siberian taiga zone using Landsat imagery: Implications for methane emissions».

We have added information about ecosystem area change in comparison to SHI map: «In addition, wetland ecosystem areas have significantly changed in comparison to SHI map (Peregon et al., 2009); in particular, we obtained 105% increase of spatial extent of high-emitting ecosystems 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 met them for 8 years of regular field studies. They occupy small areas and 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 (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, we just cannot afford data of such coverage. Despite the method is very time-consuming and expensive, 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 have already been 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 part at the end of «Challenges and future prospects» section: «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).»

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 generally suggested that the smallest observable feature that can be identified need to be 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.

«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.

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 better in Russia: many 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; Walter, 1977; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Masing et al., 2010). They resulted in developing the conventional (for Russia) classification of wetland macrostructural elements. Majority of these 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 adopted this convention («wetland complexes» typology). As far as we know, it was published in detail only in Russian (Usova, 2009).

In the case of microstructural elements, the classification of «microlandscape» types made in (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 classification. However, typology made on the base of West Siberian field studies were found to be the most appropriate for this exact region.

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 with large hollows. All three RHC types have its own spectral signatures. So initially, we designated three RHC complexes and then joined them into single class, because their accuracies were lower than the accuracy of combined RHC class. We have extracted this information from the scenes using high-resolution images available from Google Earth; we also used extensive field data recorded in 28 test areas. To make it clearer, we have added some information about subtypes to the Table 2 from the paper.

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. 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, so they have its own spectral signatures, which are the most distinct when the ratio between wooded and open wetland ecosystems (ridges and hollows) is equal within the patterned complex.

Water table information in patterned wetlands is taken into account through the estimation ridge/hollow ratios using high-resolution images. 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. We have added this information to Table 1 from the paper. 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).

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 vegetation of the West Siberian plane 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 the most inundated areas (even with grass vegetation) with the water level up to a few cm below the soil surface. They were empirically determined for each scene by testing various candidate values in Quantum GIS.»

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

Revised:

«As a result, we had to compliment training sample set by relying mostly on high-resolution images available on Google Earth. They come from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics. Multispectral images, which are reduced to visible bands (blue, green, red) and resolution of 1-3 meters, were used. There were limited or no meta-data available regarding image acquisition dates and spectral transformations.»

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 measured methane fluxes in all microforms including hummocks.

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.»

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?

Main criteria for training data is the homogeneity of training samples; land-cover mixtures and heterogeneous areas are avoided. Thus, we tried to find homogeneous RHCs and RHLCs at high-resolution images and designated them as training areas at Landsat images. The boundary conditions between classes were mathematically calculated using maximum likelihood algorithm during the classification process.

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 not important for methane inventory. It is also seems unimportant what is threshold cover of lakes to classify wetland complex as RHLC but not RHC. When complexes are already defined on the certain image, it is easy to calculate exact values of lake cover in RHLC using high-resolution (1-3 m) images. Strictly speaking, estimate of lake area relative coverage is not a prior to wetland complexes area calculation, but a posterior.

Revised: «During wetland typology development, we made several assumptions. First, the wetland complexes were considered as individual objects, while they usually occupy a continuum with no clustering into discrete units, so the boundaries between classes are based on assumptions. However, it has limited impact on methane inventory, because relative area proportions of wetland ecosystems can be estimated at the high resolution classification step for any given boundaries using images of 1-3 m resolution.»

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 already 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 measurements would grow exponentially.

We have added this paragraph to the end of «Wetland typology development» section: «The conception of wetland ecosystems seems to be reasonable for CH_4 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 upscale measurements separately for southern, middle and northern taiga. We take into consideration water table level and trophic state, when we map vegetation cover using high-resolution images. However, we do not consider any spatial elements as hummocks and tussocks within wetland ecosystems. This approach introduces some uncertainty in regional methane emission estimate, which was evaluated by (Sabrekov et al., 2014). However, it is not possible to provide reliable estimates of methane fluxes on more detailed spatial scale due to number of measurements. On the contrary, accounting spatial variability at wetland ecosystem scale required about 100 flux measurements in each ecosystem type in every zone (Sabrekov et al., 2013).»

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_20 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»: «…and third, provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, NEE, biomass, etc) and the model adequacy assessment.»

14 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.

15 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. Our chamber measurements of pools from middle taiga to the north showed very low fluxes (less than 0.5 $mgCH_4/m^2/h$). Bubble traps also did not reveal any substantial fluxes.

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 have revised the text to make it clearer: «Several vegetation indices was tested to map them; however, the best thresholding result was produced by Landsat thermal band. Many of the errors were also arranged along the tundra boundary, related to the lack of ground truth data and worsened by the high landscape heterogeneity. However, those small areas were mainly correspond to palsa complexes and do not make a substantial contribution to the CH4 flux estimation.»

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Wetland mapping of West Siberian taiga zone using Landsat imagery: Implications for methane emissions

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

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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, relative areas of wetland ecosystems within each wetland complex of the final map using were estimated high-resolution images. Accuracy assessment based on 1082 validation polygons of 10×10 pixels indicated an overall map accuracy of 79%. The total area of the 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, occupying 33% of the domain, followed by forested bogs or “ryams” (23%), ridge-hollow-lake complexes (16%), open fens (8%), palsa complexes (7%), open bogs (5%), patterned fens (4%), and swamps (4%). Various oligotrophic

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 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 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). 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 mixed pixels greatly decrease the accuracy of these products. 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, surface water 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).

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: (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: 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)

Modellers are in need for a global version of the high-resolution wetland map that not only delineates wetlands but also identifies the major sub-types to which different environmental parameters could potentially be applied (Bohn et al., 2015). Several wetland maps have been used to define the wetland extent in WSL, however their application to NPP and methane emission inventories was accompanied by difficulties due to simplistic classification scheme, limited ground truth data and strong generalization of classes. The only 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 or wetland ecosystems using Landsat images and aerial photographs for five test sites. However, the limited amount of fractional coverage data and coarse resolution introduce large uncertainties in upscaling methane fluxes (Kleptsova et al., 2012).

Удалено: should be able to draw upon

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

Our long-term goal is to develop a multi-scale approach for mapping Russian wetlands using Landsat imagery with a resolution of 30 m so that the results can better meet the needs of land process modelling and other applications concerning methane emissions from peatlands. In this study, the WSL taiga zone was chosen as the primary target for the land cover classification due to the abundance of wetlands. The objectives were threefold: first, to develop a consistent land cover of peatland classes and its structural components; second, to understand the spatial distribution of different wetlands and their linkage with other land units; and third, to provide the foundation for environmental parameter upscaling (greenhouse gas inventories, carbon balance, NPP, NEE, biomass, etc) and the model adequacy assessment.

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2 Materials and Methods

2.1 Study Region

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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 from 62-89°E to 53-73°N. Because of its vast expanse and flat terrain, the vegetation cover of the Lowland has clear latitudinal zonation. According to Gvozdetsky (1968), the taiga zone is divided into three geobotanical subzones: northern taiga, middle taiga and southern taiga. It 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

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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 favourable conditions for wetland formation. 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 WSL peatlands, their development and sensitivity to climatic changes was made by Kremenetski et al. (2003).

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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.

2.2 Classification methodology

No single classification algorithm can be considered as optimal methodology for improving vegetation discrimination and mapping; hence, the use of advanced classifier algorithms must be based on their suitability to achieve certain objectives in specific areas (Adam et al., 2009). Because mapping over large landscapes typically involves many satellite scenes, multi-scene mosaicking is often used to group scenes into a single file 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 with similar vegetation and hydrological conditions is limited. As a result, spectral discrepancy that is difficult to overcome emerges even within wetland types. In this study, it was considered that the advantages of consistency in class definition within scene-by-scene classification greatly exceed the disadvantages of edge matching and processing labor. Thus, our entire analysis was performed on a scene-by-scene basis, as conducted by Giri et al. (2011) and Gong et al. (2013).

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The scene selection procedure was facilitated because the possibility to adequately smooth the slight inconsistencies between images by specifying training sites in overlapped areas. Ideally, it is better to use data acquired in the same year or season, especially in the peak of the growing season (July), for wetland identification. However, the main complication was the low availability of good quality cloudless images of WSL from those periods. Scenes collected earlier than the 2000s were considered outdated due to land cover changes, so they were used as substitutes for places where no suitable imagery could be found. Landsat-7 images received after 2003 were not used due to data gaps, and Landsat-8 was launched after the beginning

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mapping procedure. Finally, we collected 70 compatible vegetation scenes during the peak of the growing seasons in different years. Majority of the images were Landsat 5 TM scenes from 2007.

The overall work flow involves data pre-processing, training and test sample collection, image classification on a scene-by-scene basis, the 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 al., 2001). All of the images were re-projected onto the Albers projection. Because the vegetation of the West Siberian plane 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 the most inundated areas (even with grass vegetation) with the water level up to a few cm below the soil surface. They were empirically determined for each scene by testing various candidate values in Quantum GIS. 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 bands except the thermal infrared band were used.

Training data plays a critical role in the supervised classification technique. Representative data collection 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 an extensive dataset of botanical descriptions, photos, pH and electrical conductivity data from 28 test sites in WSL (Glagolev et al., 2011). Due to the great expanse of WS, we still have a lack of ground truth information, which hampers training dataset construction. As a result, we had to compliment training sample set by relying mostly on high-resolution images available on Google Earth. They come from several satellites (QuickBird, WorldView, GeoEye, IKONOS) with different sensor characteristics. Multispectral images, which are reduced to visible bands (blue, green, red) and resolution of 1-3 meters, were used. There were limited or no meta-data available regarding image acquisition dates and spectral transformations. The processing started with mapping scenes where ground truth data and high-resolution images are extensively available,

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Удалено: was used to mask the most inundated areas including water bodies

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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: 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

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Удалено: They were used as an additional source of information.

so the classification results could be checked for quality assurance, then 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 in (Gong et al., 2013) for training sample selection: (i) the training samples must be homogeneous; land-cover mixtures 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 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 future classification performance (Jain et al., 2000). When accuracy of more than 80% overall was attained with no fields showing unreasonable or unexplainable errors, the classification process was started.

The spectral classes that were discriminated during the supervised classification were generalized into 9 wetland complexes. Classification mismatch in overlapping areas was minimized by collecting training samples from overlapping areas until satisfactory results were achieved. Classified images and area calculations were combined using the GRASS module in Quantum GIS. Wetlands and water bodies that are only of one or a few Landsat pixels in size were found, and many of these sites appear to be noise. Therefore, we applied noise filter 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 has the highest error contribution and 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 an advanced technique to improve the estimate of the regional CH_4 flux 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 yield reliable upscaling, we assigned 7 wetland ecosystems in our classification scheme (Fig. 1; Table 1).

However, wetland ecosystems generally have sizes of from a few to hundreds of meters and cannot be directly distinguished using Landsat imagery with 30-meter resolutions. Therefore,

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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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we developed a second wetland typology that involves 9 mixed “wetland complexes” (Fig. 1; Table 2). The assigned wetland complexes should meet the following criteria: (i) distinguishability by Landsat images, and (ii) abundance in the WSL taiga zone. All these complexes were described in detail in a number of Russian studies (Katz and Neishtadt, 1963; Walter, 1977; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompass wooded, patterned, open wetlands and water bodies.

To merge typologies, we estimated relative areas of wetland ecosystems within each of wetland complexes 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 corresponding to these areas were classified in Multispec v.3.3. An unsupervised ISODATA classification was done on the images specifying 20 classes with a 0.95 confidence interval. 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 to facilitate applying the resulting map to upscaling CH$_4$ fluxes. The approach is similar to described 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. First, the wetland complexes were considered as individual objects, while they usually occupy a continuum with no clustering into discrete units, so the boundaries between classes are based on assumptions. However, it has limited impact on methane inventory, because relative area proportions of wetland ecosystems can be estimated at the high resolution classification step for any given boundaries using images of 1-3 m resolution. Second, the classification schemes include all water bodies, although many (rivers, creeks, and large lakes) are not structural components of wetlands. Based on field knowledge, we assumed that all of the water bodies that arose from peatland development have sizes less than 2×2 Landsat pixels. These water bodies are represented by wetland pools, waterlogged hollows and watercourses, 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.

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.¶
However, wetland ecosystems generally have sizes of approximately 1-10 meters and cannot be directly distinguished using Landsat imagery with 30-meter resolutions, with a few exceptions. When the objects in the scene become increasingly smaller relative to the resolution cell size, they may no longer be regarded as individual objects. The reflectance measured by the sensor can be treated as a sum of the interactions among various classes of scene elements as weighted by their relative proportions (Lu and Weng, 2007; Strahler et al., 1986). Therefore, we developed a second wetland typology that involves 9 mixed “wetland complexes” and then estimated the fractional area coverage of the wetland ecosystems within each of them (Fig. 1; Table 1). The assigned wetland complexes should meet the following criteria: (i) distinguishability by Landsat images, and (ii) abundance in the WS taiga zone. All these complexes were described in detail in a number of Russian studies (Katz and Neishtadt, 1963; Walter, 1977; Romanova, 1985; Liss et al., 2001; Lapshina, 2004; Solomeshch, 2005; Usova, 2009; Masing et al., 2010) and encompass wooded, patterned, open wetlands and water bodies.¶
To estimate the fractional area coverage of the wetland ecosystems, we selected

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Удалено: so the boundary between classes is an assumption. However, it has no impact on methane inventory, because relative portions of wetland ecosystems can be estimated posteriorly for any boundaries using images of 1-3 m resolution.

Удалено: floodplain areas were not taken into account aside from misclassification cases

The conception of wetland ecosystems seems to be reasonable for CH_4 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 upscale measurements separately for southern, middle and northern taiga. We take into consideration water table level and trophic state, when we map vegetation cover using high-resolution images. However, we do not consider any spatial elements as hummocks and tussocks within wetland ecosystems. This approach introduces some uncertainty in regional methane emission estimate, which was evaluated by (Sabrekov et al., 2014). However, it is not possible to provide reliable estimates of methane fluxes on more detailed spatial scale due to number of measurements. On the contrary, accounting spatial variability at wetland ecosystem scale required about 100 flux measurements in each ecosystem type in every zone (Sabrekov et al., 2013).

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Удалено: Forth, 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 more detailed spatial scale.¶

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 proved to be noticeable even at the global scale. 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 coverage is larger than the total 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.

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As summarized by Sheng et al. (2004), the majority of previous local Russian studies estimated the extent of the entire WS's mires to be much 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 was characterized by a lack of field data in remote regions and a high generalization level and only considers economically valuable wetlands with peat layers deeper than 50 cm.

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Our peatland coverage is most 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 too generalized and missing important details on the wetland distribution (Fig. 3). SHI map was based on aerial photography, which is not reasonable for mapping and monitoring wetland vegetation on a regional scale because it is too costly and time-consuming to process (Adam et al., 2009). 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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In addition, wetland ecosystem areas have significantly changed in comparison to SHI map (Peregon et al., 2009); in particular, we obtained 105% increase of spatial extent of high-emitting ecosystems 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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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 the "Lakes and rivers" class), RHCs prevail in WS's taiga, occupying 32.2% of the domain, followed by ryams (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 oligotrophic environments 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 with surface water during the non-frozen summer season.

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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). The knowledge regarding the spatial distribution of different wetlands facilitates mapping and further understanding of their linkage with each other and other land units. To visualize the regularities of the wetland distribution, we divided the entire area into 0.1°×0.1° grids and calculated the wetland ecosystem to the total cell area ratios for each grid (Fig. 4) using fractional coverage data from Table 2.

Mire coverage of WSL's northern taiga (between 62°N and 65°N) is approximately 36%. Because of the abundance of precipitation, low evaporation and slow runoff, the northern taiga is characterised 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 kilometres from east to west and is located between 61.5°N and 63°N. Peatland and water bodies cover up to 70% of the territory, forming several huge peatland-lake complexes that are divided by river valleys. Northward, the slightly paludified "Sibirskie Uvaly" (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 (approximately 59-62°N), where mires occupy 34% of the area. Large wetland systems commonly cover watersheds and have a convex dome with centres that are 3 to 6 m higher than the periphery. These environments have peat layers that are several meters deep and are composed of sphagnum peat with the small addition of other plants. The wetland ecosystems here have strict spatial regularities. Central plateau depressions with stagnant water are represented by RHLCs. Different types of RHCs cover better-drained gentle slopes. The most drained areas are dominated by ryams. Poor and rich fens develop along the wetland's edges, with low lateral water flow and relatively high nutrient availability. Wooded swamps usually surround peatland systems.

The wetland extent reaches 28% in WS's southern taiga area (approximately 56-59°N). Vast peatland systems are composed of raised bogs represented by ryams and RHCs with huge open and patterned fens between them. 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 in a stepwise fashion due to the abundance of carbonate soils and higher nutrient availability. 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

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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: 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).

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 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 ground truth information. The confusion matrix (Table 4) was used as an effective way to represent map accuracy as the individual accuracies of each category are plainly described along with both the errors of inclusion and errors of exclusion (Congalton and Green, 2008). We found that the accuracies for different land-cover categories varied from 62 to 99%, with the lake and river, ryam, and RHC areas classified the best and open bogs and patterned fens the most confused. Some errors occurred along boundaries and 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.

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Удалено: Misclassifications usually occurred between neighbouring classes with greater similarities in their environmental parameters, which exhibit only minor distortions in map applications.

Wetland complexes within large wetland systems have highest classification accuracies. In contrast, the uncertainties are particularly high for the 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 produced by Landsat thermal band. Many of the errors were also arranged along the tundra boundary, related to the lack of ground truth data and worsened by the high landscape heterogeneity. However, those small areas were mainly correspond to palsa complexes and do not make a substantial contribution to the CH_4 flux estimation.

Misclassifications usually occurred between neighbouring classes similar in environmental parameters, which introduce only a minor distortion in map applications. Patterned fens and open bogs were classified with the lowest producer’s accuracy (PA), which was 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. Open bogs often have tussock shrub cover with sparse pines, increasing the frequency of misclassification as RHCs and ryams. 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

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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. Swamps were commonly confused with forests. 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 seldom confused with RHLCs, especially when represented by a series of small lakes or waterlogged hollows that are divided by narrow necks on the land. Floodplains can also be classified as lakes and rivers when the image corresponds to the most inundated period after snow melt (11 polygons). RHCs and ryams were accurately identified due to the abundance of these categories in the study region and their high spectral separability.

Generally, we achieved a reasonable accuracy of 79% for such a large and remote area. However, this value seems to be slightly overestimated, because high-resolution images are not always effective in distinguishing similar environments that differ in their nutrient supply level.

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, correctly distinguishing continuous series of wetland complexes complicated by seasonal variations remain one of the largest challenges. Wetlands become the most inundated after snow melting or long rainy periods, resulting in the transformation of oligotrophic hollows and fens into waterlogged hollows. In this case, RHCs and patterned fens can develop turn into RHLC because of the flooding (Fig. 1: areas in RHCs with brown Sphagnum cover usually develop into waterlogged hollows after flooding). Swamps typically dry up after drought periods, and their environmental features become similar to those of non-wetland areas. In contrast, the huge floodplains of the Ob' and Irtysh Rivers become inundated during prolonged snowmelt floods. Interannual variability of water table level also occurs in WSL (Schroeder et al., 2010; Watts et al., 2014). Water table fluctuations are especially important for upscaling CH_4 fluxes because the areal extent of methane-emitting regions, and therefore, the total methane emission, are functions of the spatial distribution of water table depths (Bohn et al., 2007). Watts et al. (2014) underscored the importance of monitoring

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Удалено: The spectral discrimination of wetland types in complex environments is a challenging task because different vegetation types commonly possess the same spectral signature in remotely sensed images . However, the contrast between vast wetland systems and the surrounding forest areas is usually so distinct that wetlands can be adequately identified by the summer season images, in which the discrimination between wetlands and forests does not impose a serious problem (Sheng et al., 2004).

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changes in surface moisture and temperature when assessing the vulnerability of boreal-Arctic wetlands to enhanced greenhouse gas emissions under a shifting climate.

Удалено: (Adam et al., 2009)

New methodologies and protocols are needed to combine remotely sensed observations to improve our ability to monitor continuous water levels or distinguish habitat types or other characteristics of wetland environments (Kim et al., 2009). Perhaps the best opportunity in the next few years for routine measurements of inundated areas will result from PALSAR (Chapman et al., 2015; Clewley et al., 2015). The use of additional radar data to map the most inundated areas will be especially useful for CH_4 flux upscaling because only wetland ecosystems with high water levels contribute to the regional flux, while the effects of dryer ecosystems (ryams, ridges and palsa hillocks) can be neglected (Glagolev et al., 2011; Sabrekov et al., 2014).

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 and extent in WS’s wetlands. Simplistic monitoring measurements 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 were not published. These measurements are of special importance for the northern taiga zone, where small shallow lakes and waterlogged hollows with fluctuating water regimes cover huge areas.

Удалено: optical and radar data

The scarcity of reliable reference data and subsequent lack of consistency limit the accuracy of land cover information that are derived from satellite imagery (Homer and Gallant, 2001). The use of ancillary data can largely improve the accuracy of maps (Congalton et al., 2014); however, more reliable classification accuracy comes with significant costs regarding data, local knowledge, and detailed field data. The next step in improving mapping should rely on the acquisition of ground truth data from the most ambiguous wetland landscapes and remote regions. 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).

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 Russian wetlands using Landsat imagery, with the general goal of supporting the monitoring of wetland resources and upscaling the methane 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 features 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 revaluation of the total CH_4 emissions from the entire region is expected.

Удалено: describe

Удалено: WS

Удалено: Although 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: 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%, which is reasonably good 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. There is a need for installing water level gauge network covering the most abundant wetland types.

Удалено: most ambiguous

Удалено: embracing

Удалено: at least

Our new Landsat-based map of WS's taiga wetlands provides a benchmark for validation of coarse-resolution global land cover products and for assessment of global model performance in high latitudes. Classification scheme geared towards improving methane emissions on methane inventory but is applicable for the upscaling of other environmental parameters.

Удалено: was oriented

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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 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 (see (Glagolev et al., 2011) and references there)

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)

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

Wetland complexes	**Short description**	**Wetland ecosystems**
	Wooded wetlands	
Pine-dwarf shrubs-sphagnum 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. Patterned fens with small, medium, and large hollows can be arranged within the class.	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 characterized by high productivity and includes sedges, herbs, hypnum and brown mosses.	F: 100%
	Water bodies	
Lakes and rivers	All water bodies larger than 60×60 m^2, so they can be directly distinguished by Landsat images.	W: 100%

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 ...

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: 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 …s characterized by higher ...

Удалено: This type consists of a…ll water bodies larger than 602…2 …0 m^{2}Landsat pixels… which ...

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*	

Удалено: 2

Удалено: W

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

Удалено: 3

Real classes Estimated classes	Non-wetland	Lakes and rivers	RHLC	Ryams	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*
Ryams	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*		

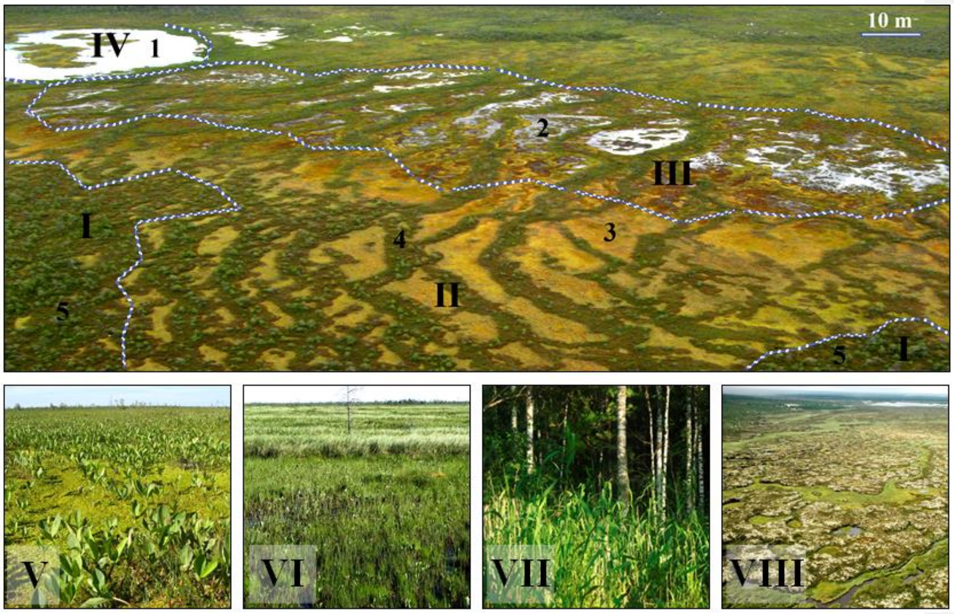

Figure 1. Wetland complexes (I – Ryam, II – Ridge-hollow complex or RHC, III – Ridge-hollow-lake complex or RHLC, IV – Lakes and rivers, V – Open fens, VI – Patterned fens, VII – Swamps, VIII – Palsa complexes) and ecosystems in WSL (1 – Open water, 2 – Waterlogged hollows, 3 – Oligotrophic hollows,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

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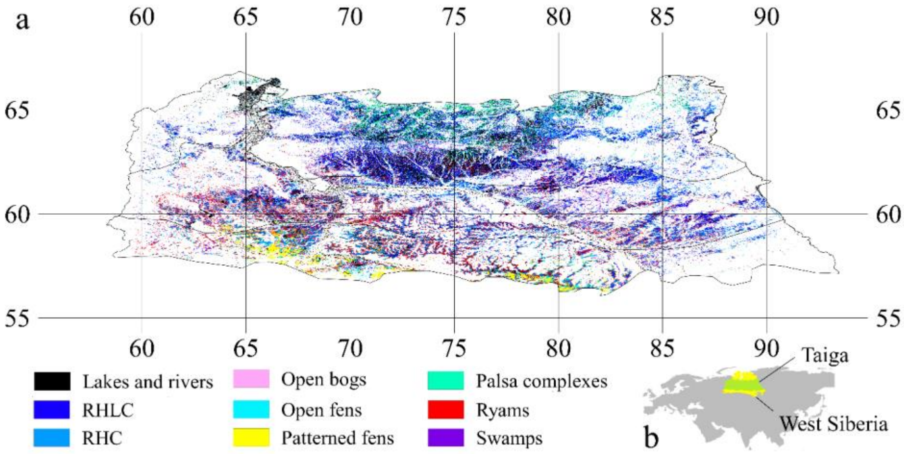

Figure 2. Wetland map (a) of the WSL taiga zone (b; yellow – WS, green – taiga zone)

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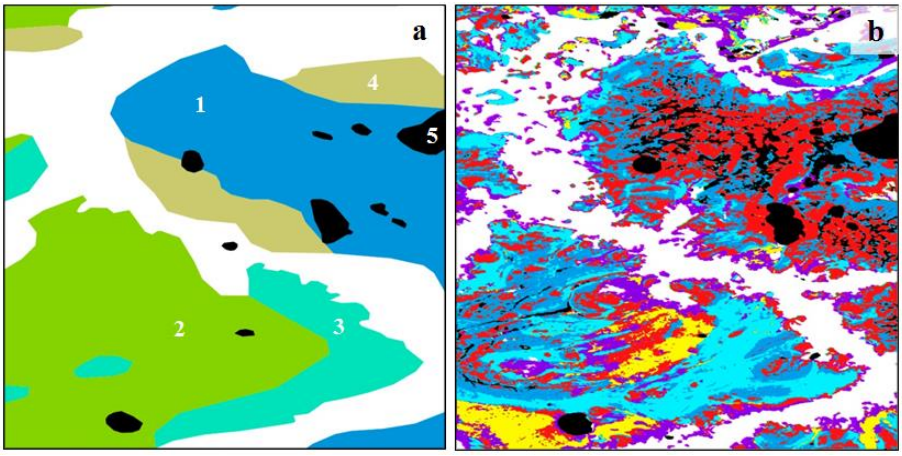

Figure 3. Comparison of wetland classifications: a – SHI map (1 – Sphagnum-dominated bogs with pools and open stand of trees, 2 – ridge-hollow, ridge-hollow-pool and ridge-pool patterned bogs, 3 – forested shrubs- and moss-dominated mires, 4 – moss-dominated treed mires, 5 – water bodies), b – this study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

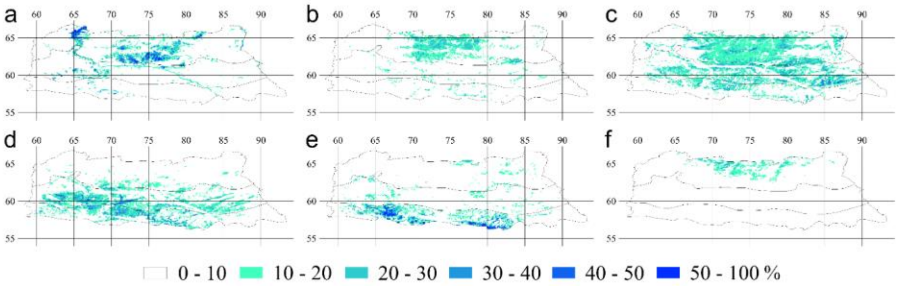

Figure 4. Wetland ecosystem areas for 0.1°×0.1° (% from the total cell area): a – open water, b – waterlogged hollows, c – oligotrophic hollows, d – ryams, e – fens, f – palsa hillocks; the distribution of ridges is not represented because it is quite similar to the oligotrophic hollow distribution;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