CLASSIFICATION OF BOREAL MIRE BIOTYPES WITH HYPERSPECTRAL AIRBORNE HYMAP IN FINLAND

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ABSTRACT:

Spatial information on mire biotypes would be an asset in inventorying mires for protection purposes and in monitoring changes in mire diversity caused by artificial regulation of mire hydrology, atmospheric deposition, and global change. We took a data-driven approach to explore the potential of airborne imaging spectroscopy data in determining plant communities of pristine treeless northern boreal mires in Finland (65˚57'N, 24˚29'E). It was hypothesized that plant species distribution and soil nutrient regimes are determining factors in spectral reflectance of mires, thus mires could be classified in several plant associations from medium resolution (5 m) imaging spectroscopic data. The objective was to discover the optimal ecological meaningful mire class number for our remotely sensed dataset. Minimum noise fraction transformation of geocoded and atmospherically corrected hyperspectral HyMap data (437-2485 nm) was subjected to non-metric multidimensional scaling (NMDS) and unsupervised neural networks. The performance was tested against a field inventory of plant species, dielectric (ε) measurements of soil water content and electrical conductivity (σ) of soil nutrient regimes. NMDS ordination revealed nutrient-poor *Sphagnum fuscum* bogs with abundance of *Sphagnum fuscum*, *Rubus chamaemorus*, *Empetrum nigrum* and *Vaccinium uliginosum* to be associated with high NIR and NDVI, and spectrally deviate from nutrient-rich sedge fens with *Betula nana*, *Carex lasiocarpa*, *Carex* sp., litter and *Menyanthes trifoliata*. The NMDS also indicates that *Sphagnum angustifolium*, *S. lindenbergii* and *S. papillosum* dominated low sedge fens could be distinguished separately by spectral data. Classification to seven classes with Kohonen's self organizing maps (SOM) outperformed the fuzzy neural networks and *k*-means clustering producing the highest separability of classes in plant species coverages. The SOM classes were combined to produce a three class ('nutrient-poor *Sphagnum fuscum* bog', 'nutrient rich sedge fen' and 'nutrient-poor low sedge fen') thematic presentation of boreal mires. The study serves as a step towards an operational mire surface monitoring system based on imaging spectroscopic data which further improvement could be geared towards subpixel analysis and scale dependency of ecological classification detail in pixel based approaches.

1. INTRODUCTION

Presently, mires are attractive as objects of research since they are storages of green house gasses, major biodiversity reserves and under pressure due to exploitation for energy production, chemical industry and horticultural use. Global warming is predicted to have impacts on mire hydrology and the resulting changes may act as a major triggering mechanism of greenhouse gas release. Pristine mires preserve many rare and endangered species thus potential further protection should focus on the most nutrient- and species-rich sites (Aapala, 2001). Mapping of surface properties, including soil water and nutrient regimes and plant species distribution on pristine mires, would be desired from the perspectives of conservation, modelling carbon cycling globally and inventorying mire biodiversity. Such extensive wetland inventory or monitoring data is presently not yet available nationwide.

Remote sensing could serve as a tool for peatland classification and monitoring. Usability of remotely sensed data in wetland research has already been demonstrated through research involving interpretation of aerial photographs (e.g. Tuominen and Aapala, 2001), coarse resolution optical satellite data (e.g. Bronge and Näslund-Landenmark, 2002) and imaging satellite radar (e.g. Grenier et al., 2007). Classification success is mainly determined by the level of classification detail (number of classes and their ecological description) a certain scale data set is processed to. Mineral soil can be well (80-90% accuracies) distinguished from peatlands by Landsat TM, Landsat MSS, NOAA AVHRR and aerogeophysical data (Lahti and Häme, 1992), through a combination of digitized aerial photographs and Landsat TM (Holopainen and Jauhiainen, 1999; Xinglai and Sheng, 2005), and by Landsat ETM+ (Haapanen and Tokola, 2007). When the number of classes increases to mire site type level or to higher number of biotopes, and higher resolution data such as digitized aerial photographs, airborne hyperspectral imaging spectroscopy and satellite SPOT data is used classification accuracies decrease (60-80% overall accuracies; Grenier et al., 2008; Xinglai and Sheng, 2005; Arkimaa et al., 2005). Deckha et al. (2002) discovered that processing of Ikonos-2 into wetland assemblages with a broad wetland classes produced lower accuracies than a more detailed vegetation community level classification. This leads one to think that each dataset, based on their spectral, spatial and temporal resolution has an optimal class level when pixel-based (hard) classifiers are used. The objective of this was to study the optimal class hierarchal level which airborne hyperspectral data can be processed to produce vegetation assemblages

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that could aid environmental planning and mire inventories. Compared to visible and near-infrared data improved spectral segregation of mire plant assemblages is hypothesized to be achieved with hyperspectral data including also the short-wave portion of the spectrum.

2. MATERIALS AND METHODS

2.1 Keminmaa study area

The study is located in one of the most peatland-rich landscapes of Europe in Perä-Pohjola aapa mire zone (see fig. 2; Ruuhijärvi and Hosiaisluoma, 1988). Aapa mires are characterized as a minerotrophic vegetation-ecological mire complex type with a concave surface i.e. the centre of the mire is situated lower than the surrounding mineral soil. According to the Geological Survey of Finland (GTK) peat resource database, fens (finnish: neva) are the most common mire type in the Keminmaa study area: mesotrophic low-sedge bogs comprise 41.2% of the GTK inventoried mires, tall-sedge fens 8.8%, flark fens 4.6%, and herb-rich sedge fens 2.7%, whereas oligotrophic *Sphagnum fuscum* bogs cover 26.3% and low-sedge bogs 2.3% (site types according to Laine and Vasander, 2005).

2.2 Hyperspectral, GIS and field data

The HyMap^{TM} imaging spectrometer (Cocks et al., 1998, Hyvista Corp., Sydney, Australia) was flown over an area of 1100 km^2 in a Donier 288 on the 29th of July, 2000, starting at 11.35 am local time. A swath width of 2 km and 5 m spatial resolution were achieved with a 60˚field of view, 2.5 mrad along and 2.0 mrad across track instantaneous fields of view, and 278 km/h ground speed at 2 km flight altitude. The instrument was programmed to record 126 10-nm-wide bands in 437-2485 nm.

Field data was gathered in 5-by-5-meter sampling plots the locations of which were randomized by creating a 250 m squared point grid over the study area. The final plots were chosen on treeless mires (Finnish National Land Survey, NLS, 1:20 000 GIS database) within a distance of 500 m from the road network to ensure that they were easily accessible on foot (115 plots). The surface layer ε (as a measure of volumetric water content) was measured with an electrical capacitance probing probe (Adek Ltd., Tallin, Estonia) and σ (peat water solute content) with a galvanic conductivity fork (Geological Survey of Finland) in each corner and centre of the plot similarly to plant species inventory (1 m^2 plots). Species coverages were estimated as percentage proportions from above rather than bottom and field layers separately in order to better correlate species to remotely sensed data. Values were averaged to represent each 5-by-5-m plot and plot centers were located with GPS. Sampling plots with canopy coverage more than 7 % were later eliminated from the dataset which resulted in a final sample size of 84 sampling plots. The most common species with maximum coverage of 20% or more were subjected to statistical analysis as they can be expected to have significant impact on HyMap spectra.

2.3 Preprocessing, statistical analyses and classification

Geometric rectification was performed with PARametric GEocoding (versio 1.3, ReSe Applications Schläpfer, Remote Sensing laboratories of the University of Zurich, Zurich, Switcherland; Schläpfer, 2001) elevation, position and a high number of tie points (> 50 points/ flight stripe) as inputs because attitude data from the initial measurement unit was not available. Atmospheric correction and BRDF correction with nadir normalization procedure was done with ATCOR4 (Richter, 2003) with five pseudo invariant features as inputs. Stripes were mosaiced as continuous data, and the number of bands was reduced to 109 including 477-862 nm, 882-1326 nm, 1472-1795 nm and 1999-2432 nm. Data over the study area was extracted from a larger dataset (see Arkimaa et al., 2005) and under a mask of treeless mires (according to NLS GIS database). Minimum noise fraction (MNF) bands 1-10 were chosen for further analysis because their eigenvalues were greater than five. The MNF and spectral values were extracted from the HyMap data under corresponding sample plot locations.

The NMDS (Kruskal, 1964) is a visualization and data mining technique which explores similarities and dissimilarities in data. We analyzed field measured vegetation composition, σ and ε, and HyMap bands and NDVI relative to HyMap MNF bands with NMDS using Bray-Curtis dissimilarities (Bray and Curtis, 1957). Significances of the correlations with spectral data were tested with 5000 permutations. The 5-m MNF bands were also resampled to 10 m pixel size with the nearest neighbour algorithm, and the NMDS ordination was set up with both data. The appropriate input MNF bands and pixel size for unsupervised classification were chosen based on the NMDS.

HyMap data was classified with three unsupervised classifiers: *k*-means clustering implemented in ENVI (Research Systems Inc., Boulder, CO, U.S.A.), fuzzy neural networks in GeoXplore (v. 4.1, University of Nevada, Reno, U.S.A.; Looney et a., 2004) available as an ArcSDM (Geological Survey of United States, Geological Survey of Canada, Sawatzky, Raines and Bonham-Carter, 2007) extension in ArcMap (ESRI, Redlands, U.S.A.) and Kohonen's self organizing maps (SOM; Kohonen, 2001) coded in SOMToolbox (Neural Networks Research Centre, Laboratory of Computer and Information Science, Helsinki University of Technology) and used with SiroSOM graphical interface (Commonwealth Scientific and Industrial Research Organisation, Australia). With each classifier three results having 5, 7 and 9 classes were produced. The classification results were referenced to ground observations by calculating mean values of field data within each class. Vegetation differences between classes were quantified with multivariate analysis of variance (MANOVA) using Bray-Curtis distance matrices (Bray and Curtis, 1957; Anderson, 2001) to find the classification which would explain most of the deviation between classes with plant species. The coverages of the most common species were used as inputs in MANOVA. The statistical analyses were accomplished in R version 2.8 (R Development Core Team 2008) with Vegan version 1.15 (Oksanen et al., 2008).

3. RESULTS

According to the plant species inventory *Sphagnum* species were the most dominant in the Keminmaa study area having 35.7% mean coverage overall (maximum coverage 81%) *S. angustifolium* being the most common (23.5%) and *S. fuscum* the second most common (9.2%). *Carex* species are the second most common species group with 7.7% mean coverage followed by *Rubus chamaemorus* (6.7%), *Empetrum nigrum* (5.9%), litter (5.3%), *Betula nana* (5.2%) and *Menyanthes trifoliata* (4.1%). Locally other single species can cover up to 78% of a field plot.

The NMDS (fig. 1) showed the following variables to have significant correlations with the MNF ordination: MNF bands 1, 2, 4, 5, 8-10 ($p \leq 0.05$), soil σ ($p=0.005$), NDVI ($p=0.010$), spectral bands 539-1793 nm and 2083-2342 nm ($p \leq 0.01$), and *Betula nana*, *Carex lasiocarpa*, *Carex* sp., *Empetrum nigrum*, *Menyanthes trifoliata*, *Rubus chamaemorus*, *Sphagnum fuscum*, *Sphagnum angustifolium*, *Sphagnum lindbergii*, *Sphagnum papillosum*, *Sphagnum* spp., *Vaccinium uliginosum*, litter ($p \leq 0.05$). NMDS ordination based the 5 m pixel size MNF bands had only 3 MNF bands (1, 2 and 10) statistically correlated to it ($p \leq 0.05$) whereas 7 were correlated to ordination based on 10 m pixel size MNF bands. Thus we chose the 10 m MNF bands 1, 2, 4, 5 and 8-10 for further analyses and inputs for unsupervised classification. Two distinct clusters of were found in the MNF based NMDS ordination (fig. 1). Plant species *Sphagnum fuscum*, *Rubus chamaemorus*, *Empetrum nigrum* and *Vaccinium uliginosum* associated with the cluster 'nutrient poor *Sphagnum fuscum* bog'. This ordination direction was also characterized with high NDVI and spectral bands 723-799 and 1152-1324 nm. Cluster 'nutrient-rich sedge fen' is associated with *Betula nana*, *Carex lasiocarpa*, *Carex* sp., litter, *Menyanthes trifoliata* and soil σ. *Sphagnum* species *S. angustifolium*, *S. lindenbergii* and *S. papillosum* remain outside of the clusters in the MNF feature space. *S. angustifolium* is associated with HyMap bands in 570-692 nm and 1032-1123 nm.

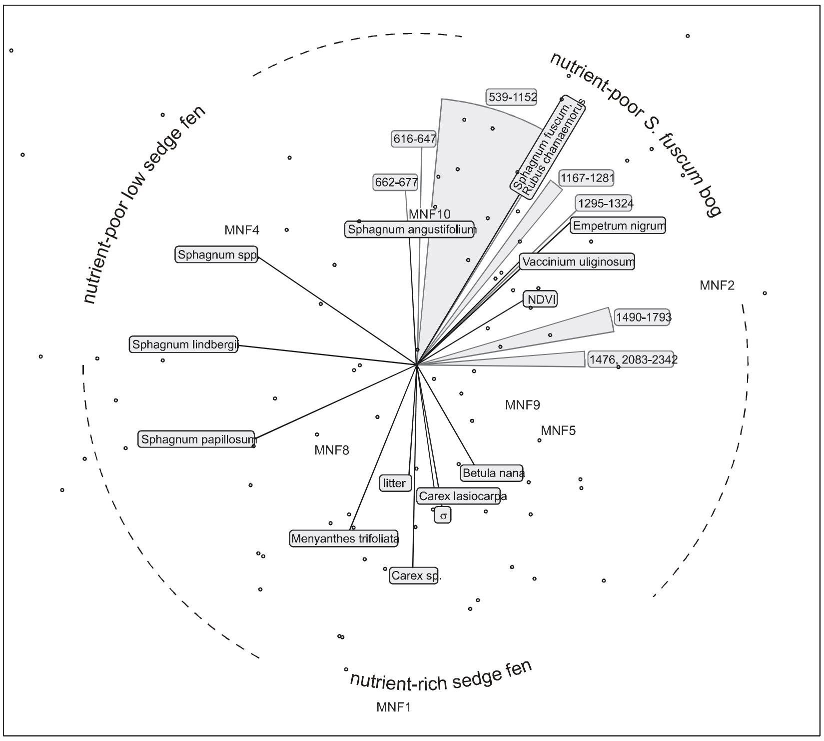

Figure 1. Nonparametric multidimensional scaling shows the illustrated *in situ* measured plant species coverages, soil electrical conductivity (σ), and HyMap calculated NDVI having significant correlation ($p \leq 0.05$) with MNF band ordination. The gray sectors represent HyMap spectral bands. Two clear clusters characterized by 1) *Sphagnum fuscum*, *Rubus chamaemorus*, *Empetrum nigrum* and *Vaccinium uliginosum* (cluster 'nutrient-poor S. fuscum bog'), and 2) *Carex lasiocarpa*, *Carex* sp., litter and *Menyanthes trifoliate* (cluster 'nutrient-rich sedge fen') can be found. Dots represent the 84 field sampling plots.

According to the MANOVA results, differences in the plant species coverages were greatest in a seven class SOM result because the ratio of between classes to within class variation was the greatest ($F=9$, $r^2=0.11$). *K*-means ($F=8.6\text{-}7.3$, $r^2=0.10\text{-}0.09$) produced classes were more separable in species coverages compared to fuzzy neural networks ($F=6.6\text{-}3.5$, $r^2=0.05\text{-}0.08$). Overall species coverage did not explain the class separation very well because the explained proportion of variances are small ($r^2= 0.05\text{-}0.11$). The SOM with seven classes was, however, chosen as the most appropriate mire classification. Number of classes was not found a critical factor for producing differences in plant species coverages.

Mean values of the *in situ* determined variables were calculated to assign each class to a thematic class (tab. 1). The seven SOM classes were combined based on the statistics as follows: 'nutrient-poor *S. fuscum* bog' (class 1), 'nutrient-rich sedge fen' (class 2, see high σ in tab. 1) and 'nutrient-poor low-sedge fen' (combined class 3). A substantial amount of overlap between the species statistics can be observed between many classes (tab. 1). The SOM classes 6, 7 and 2 are the clearest candidates of combined classes

1, 2 and 3, respectively. The combined class 3 is especially heterogeneous being a combination of several *Sphagnum* species, and could be further divided based on *Sphagnum* species dominance. The thematic map of the classes is presented in figure 2.

SOM class Combined class	1 3	2 3	3 1	4 1	5 2	6 1	7 2
Dielectric permittivity	70	73	65	66	72	65	70
Electrical conductivity (mS/m)	5.4	5.4	4.3	4.7	7.3	4.2	7.2
Canopy coverage (%)	0.2	0.0	1.6	1.1	0.4	0.8	1.0
Species coverage (%)							
Sphagnum fuscum	5.0	3.5	5.6	5.6	0.3	26	4.5
Rubus chamaemorus	2.2	5.4	10	7.9	0.5	15	2.4
Empetrum nigrum	1.0	3.7	9.1	3.5	0.4	16	4.0
Vaccinium uliginosum	0.5	1.4	10.4	1.7	1.1	4.7	2.0
Carex lasiocarpa	0.7	0.0	0.0	5.8	5.0	1.1	8.4
Carex sp.	9.0	2.4	0.4	7.7	18	1.3	12
litter	3.0	8.8	1.0	6.1	8.3	3.1	9.9
Menyanthes trifoliata	8.4	0.0	0.0	3.0	9.1	0.0	3.5
Sphagnum papillosum	13	0.0	0.1	2.6	5.0	0.1	7.0
Sphagnum lindbergii	17	0.0	1.3	7.6	7.1	0.5	0.1
Sphagnum spp.	54	59	33	41	30	17	31
Sphagnum angustifolium	24	58	30	30	15	15	19

Table 1. Mean values of *in situ* soil dielectric permittivity, soil electrical conductivity, canopy and species coverages calculated within seven self organizing map (SOM) classes. Plant species are grouped similarly to the NMDS result in fig. 1. SOM classes are combined and named as 'nutrient-poor *Sphagnum fuscum* bog' (1), 'nutrient-rich sedge fen' (2) and 'nutrient-poor low-sedge fen' (3) according to the field data.

4. DISCUSSION

The NMDS results based on HyMap spectral data demonstrated the feasibility of separating 'nutrient-poor *S. fuscum* bogs' from 'nutrient-rich sedge fens' as two clusters were formed in the MNF ordination (fig. 1). In the NMDS ordination bogs are associated with species typical to 'nutrient-poor *S. fuscum* bogs' such as *Rubus chamaemorus*, *Empetrum nigrum* and *Vaccinium myrtillus*. 'Nutrient-rich sedge fens', on the other hand, were composed of an association of *Carex lasiocarpa*, litter and *Menyanthes trifoliata* in the NMDS ordination, and had high σ indicating nutrient-rich regime. *Sphagnum* species, besides *S. fuscum*, did not coincide with these clusters which indicated a potential to discriminate *S. angustifolium*, *S. papillosum* and *S .lindenbergii* dominated mires as separate classes. In SOM classification, we combined classes dominated by these species as 'nutrient-poor sedge fens' but further division by *S.* dominance is also possible (see combined class 3 in tab. 1 and cluster 'nutrient-poor low-sedge fen' in fig. 1). The class names were given interpreting these plant associations rather than following a common site type classification system. The NMDS analysis indicated that at least three but a maximum of five clusters could be spectrally found in the data. We combined the seven class SOM into a three class thematic presentation as the seven class SOM had the highest species divergence between classes.

Spectrally *S. fuscum* bogs were especially associated with high NIR (700-800 nm and 1100-1300 nm) reflectance and high NDVI. *S. angustifolium* fens had high reflectance especially in the visible region (570-700 nm) and in NIR around 1000-1100 nm. Compared to other *Sphagnum* species, *S. angustifolium* appeared bright green in the study area thus having a high green peak and high reflectance also in NIR (Arkimaa et al. 2009). *S. fuscum,* on the other hand, was red or brown in colour, *S. lindenbergii* and *S. papillosum* yellowish-brownish green. The spectral properties of *Sphagnum* species vary between and within species according to genetics, light, nutrient and water status (Van Gaalen et al., 2007). *Sphagnum* as the most common genus in the study area was the most controlling factor in the reflectance properties of mires.

As sedge fens were located in an opposite direction in the MNF ordination from *S. angustifolium* fens and *S. fuscum* bogs, therefore their reflectance values, as well as NDVI, were lower than *Sphagnum* mires. Fens exhibited higher soil water content than bogs (see higher ε in tab. 1), although it did not became statistically significant in the NMDS ($p < 0.05$, fig. 1). The water table of most fens reaches the surface thus absorbing much of the light whereas *Sphagnum* grows above the water table. The amount of litter produced by previous years' canopy is mainly associated with coverage of *Carex lasiocarpa* in the NMDS ordination implying that most litter is produced by it. Since field observations also supported this result it was certain that the high albedo litter can have a great impact on the spectral segregation of sedge fens.

Based on our results we argue that *Sphagnum* species in the bottom layer form the basis for distinguishing between *S. fuscum* bogs, sedge fens and *Sphagnum* fens but particularly coverage of sedge, other grasses, herbaceous species and dwarf shrubs in field layer determine in what detail subclasses can be determined from bottom-field layer continuum. In pixel-based classification approach the level of classification detail is an issue of scale (Mohammed and Malthus, 2007). Although unsupervised pixel-based classifiers produced spatial clusters that could be related to species abundances and named as meaningful classes a subpixel approach could be more desirable if the distribution of spectrally distinct species were under investigation. From a perspective of medium spatial resolution data, individual mire plants and large scale plant associations (e.g. flarks) are too limited in spatial extent to be distinguished as clusters of pixels thus in subpixel analysis the abundance of species can be determined within each pixel. Plant associations which have large enough spatial extent can be mapped by classifying HyMap data. Fuzzy logic type of approach could also be logical in this case as plant community variation is continuous. In further studies, inclusion of textural attributes and vegetation indices as inputs should also be considered.

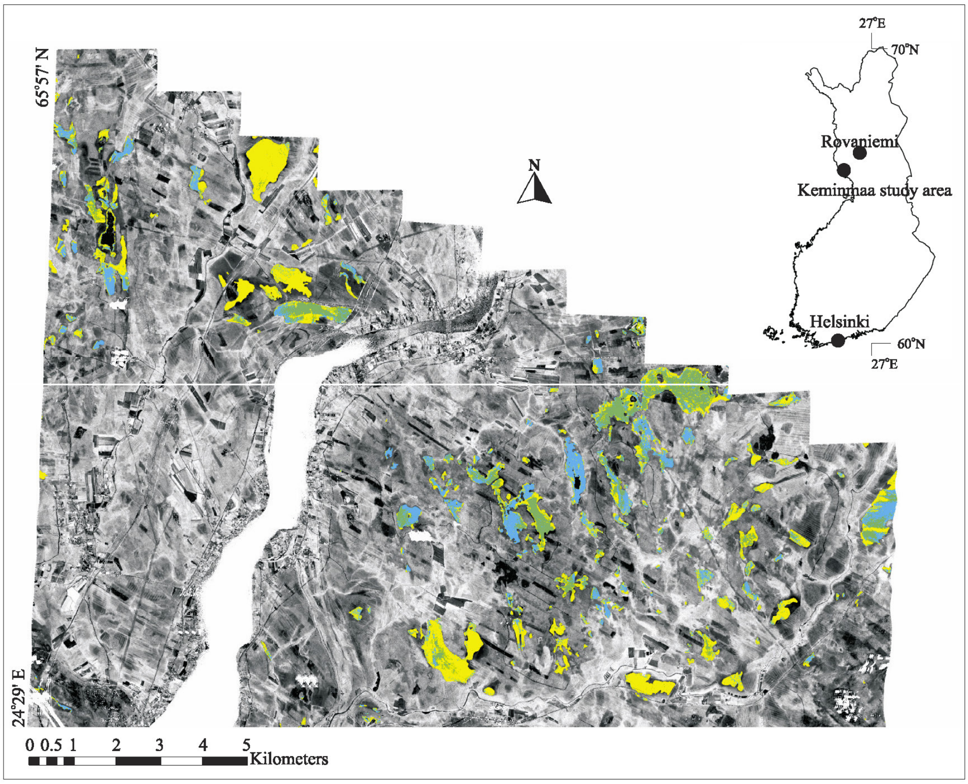

Figure 2. HyMap classification result of treeless pristine mires with SOM draped over a NDVI channel (gray scale, high NDVI = light gray). Seven classes (see tab. 1) are combined as three representing 'nutrient-poor *Sphagnum fuscum* bog' (yellow, combined class 1), 'nutrient rich sedge fen' (blue, class 2) and 'nutrient-poor low sedge fen' (green, class 3).

5. CONCLUSIONS

Of the pristine treeless northern boreal mires, the trophic extremes: nutrient-poor *Sphagnum fuscum* bogs and nutrient-rich sedge fens, could be separated by HyMap data. This classification already can be helpful for conservation planners, people conducting ecological mire inventories and even mineral prospectivity. Besides the two endmembers, different *Sphagnum* species dominated mires can be further divided with the unsupervised classification approach. Although the potential of the unsupervised method is considerable the applicability of the study is limited by the small aerial extent of our study area and limited number of mire complexes in it. To ensure the usefulness of the study in monitoring the artificial regulation of mire hydrology, effect of atmospheric emissions and global change in regional studies further investigations on the methodology are needed.

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