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Evaluation of phenospectral dynamics with Sentinel-2A using a bottom-up approach in a northern ombrotrophic peatland

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ABSTRACT

Peatlands cover very large extents in northern regions and play a significant role in the global carbon cycle by functioning as a carbon sink. Large-scale satellite based monitoring systems, such as the Sentinel-2 Multispectral Instrument (MSI), are necessary to improve our understanding of how these ecosystems respond to climate change by providing verifiable land products. For instance, satellite-based land product validation approaches can benefit from airborne hyperspectral imagery and in-situ data, which provide higher spatial and spectral resolution baselines, ideal for measuring vegetation changes (e.g. phenology, LAI) at local scales. Here, we assessed the short-term phenospectral dynamics (spectral changes indicated by specific spectral features as a function of phenology) of five ombrotrophic peatland vegetation physiognomies over four dates at the Mer Bleue bog in Canada. We took advantage of a unique remote sensing data acquisition campaign aiming to validate Sentinel-2A land products, and analyzed three spatially and spectrally distinctive datasets (i.e. field spectra, VISNIR airborne hyperspectral imagery (HSI) and Sentinel-2A imagery) over the first half of the 2016 growing season. By implementing a bottom-up approach, first we assessed the airborne HSI's capability to detect phenological changes as compared to in-situ acquired field spectroscopy measurements in a 10 ha area at Mer Bleue and evaluated the spectral features characteristic of these phenological changes. Second, over the entire Mer Bleue area (28,000 ha), we compared a series of four Sentinel-2A images to four airborne HSI mosaics (spatially and spectrally resampled to Sentinel-2A) to assess the utility of Sentinel-2A for detecting small spectral variations due to phenological changes (i.e. greening). In addition, for this second comparison, three spectral vegetation indices were derived from the Sentinel-2A images and the airborne HSI mosaics. The spectral comparisons between the airborne HSI and the field spectroscopy data revealed clear phenological changes from the airborne HSI. For instance, a closer agreement between reflectance measured by the field spectrometer and the airborne HSI spectral response was found in the visible region (450–680 nm). A greater difference however, was consistently seen in the near-infrared region (681–866 nm) across the four dates. Narrow spectral features in three regions of the visible range (global minima, red absorption, green peak), indicating changes in vegetation colour, were consistent for both datasets and with expected phenological patterns at Mer Bleue. At the landscape level, Sentinel-2A mirrored the spectral changes depicted by the resampled HSI data. However, band level, pair-wise comparisons showed significant differences ($p < 0.001$) in reflectance for each band, with Sentinel-2A exhibiting higher reflectance values than the HSI for the first three dates. Only for the last date (June 23rd) did the airborne HSI have higher reflectance values or no significant difference with the Sentinel-2A data. Overall, our three datasets captured the short-term phenological changes at Mer Bleue and have provided promising results in terms of using the Sentinel-2A MSI sensor to monitor these changes at the landscape level.

1. Introduction

Northern peatlands are a major ecosystem owing to their large extent (3% of Earth's surface) (Maltby and Immirzi, 1993), carbon storage capability over time (Gorham, 1991; Yu, 2012), and their role in the planet's climate regulation (Frolking et al., 2011; Maltby and Immirzi, 1993). In addition, peatlands provide important ecosystem services such as plant products (Chapman et al., 2003), host a unique array of biodiversity (Calmé et al., 2002) and have recently been recognized for their potential in mitigation strategies through their restoration (Leifeld

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and Menichetti, 2018). From an understanding of their biogeochemical processes to potential changes due to climate change (Bellisario et al., 1999; Frolking et al., 2011), and their high degree of exploitation and degradation (Leifeld and Menichetti, 2018), northern peatlands present a significant challenge for forecasting their future contribution to the global carbon cycle (Gorham, 1991; Moore et al., 1998). For instance, at large spatial scales (hundreds of ha) current national and global scale datasets have been shown to underestimate their extent (Krankina et al., 2008). At medium scales (e.g. single peatland areas), peatlands are exceedingly difficult to accurately map because of their complex spectral properties (Kalacska et al., 2015) and poor accessibility (Harris et al., 2015). Finally, at local scales, peatland ecosystems fundamentally possess a fragile surface structure (i.e. mosses with interspersed vascular plants) that limits the establishment of representative field plots for in-situ measurements and monitoring.

In peatlands, carbon sequestration is controlled in part by the surface structure (i.e. vegetation composition) (Belyea and Malmer, 2004), which is inherently related to hummock-hollow-lawn microtopographic elements and the proportion of vascular plants and mosses these elements comprise. Hummocks are drier elevated mounds dominated by a vascular plant overstory than lower lying, wetter hollows, which are dominated by mosses (in bogs, generally *Sphagnum* spp.) (Eppinga et al., 2008). The vertical variation in elevation between hummocks and hollows is generally < 1 m (Lafleur et al., 2005). Vegetation characterization and dynamics studies in peatlands, aimed at identifying potential climate change effects (e.g. sink or source of greenhouse gases) (Moore et al., 1998; Tarnocai, 2006), require methodological approaches that can quantify the vegetation's structural and compositional variability across different spatial and temporal scales. Thus, the spatial scale must include 'plot to landscape' level measurements that can capture the spatial heterogeneity of the vegetation (Kalacska et al., 2015), while the temporal scale must be able to capture short term (e.g. monthly) to long term (e.g. decadal) variations (e.g. phenological changes). However, capturing vegetation composition at increasing spatial scales (e.g. from cm to km) is a major challenge in northern peatlands given their structural complexity (Harris and Bryant, 2013; Kalacska et al., 2015). In-situ spectral measurements have the potential for the characterization of hollows and hummocks, in terms of their structure and seasonal phenological changes. However, given the fragile surface structure of peatlands, representative sampling based on in-situ measurements is limited. Airborne HSI with very high spatial and spectral resolutions (e.g. ≤1 m) is another potential tool for assessing plant composition and phenological changes in peatlands. However, the cost and operational challenges of multiple airborne missions could be daunting, especially when covering large areas. Lastly, newer medium spatial and spectral resolution spaceborne platforms such as Landsat-8 OLI and Sentinel-2 (MSI instrument), might be limited in detecting vegetation characteristics at higher spatial scales (≤10 m) but may be able to capture general short-period phenological changes at the landscape level due to their high revisit time.

Remote sensing methods have been shown to provide promising peatland data at different spatial and spectral scales, and have become a suitable alternative to in-situ measurements of fragile peatland ecosystems (Harris and Bryant, 2013; Sonnentag et al., 2007). For instance, their utility ranges from the development of thematic maps from medium (> 10 m and < 30 m) spatial resolution satellite imagery for quantifying vegetation extent (Krankina et al., 2008; Poulin et al., 2002), to modeling foliar pigments using field spectroscopy and airborne hyperspectral imagery (HSI) at very high spatial and spectral resolutions (≤1 m) (Kalacska et al., 2015). However, a less explored venue in remote sensing of northern peatlands is the synergistic use of multiple data sets (Harris and Bryant, 2013) for validating satellite land products. The use of multiple remotely sensed datasets for validating land products (e.g. phenology, LAI, surface temperature) in peatlands is challenging, because ideally, it requires near-coincident spatial and temporal data as changes in vegetation characteristics happen over short periods of time. Multiple remote sensing data sets require different collection methodologies, which are time consuming and expensive. Moreover, to provide a direct comparison between datasets, post processing procedures (i.e. georectification, radiometric calibration, atmospheric correction) require high levels of expertise (i.e. consistent field spectroscopy measurements, hyperspectral airborne calibration/validation, radiometric and atmospheric corrections, etc.).

In this study, we have taken advantage of unique remote sensing datasets collected between April and June 2016 from the Mer Bleue Arctic Surrogate Simulation Site (MBASSS) Sentinel-2/Landsat 8 Data Product Validation Project (Soffer et al., 2017), which included near coincident field spectroscopy data (plot level), atmospherically corrected airborne VIS/NIR CASI-1500 HSI and Sentinel-2A MSI satellite imagery (Drusch et al., 2012). By implementing a bottom-up approach (from in-situ spectral characterization to satellite imagery), we use the plot level field spectroscopy data to evaluate the capability of the airborne HSI to capture the phenological trends for part of the growing season at Mer Bleue. Then, we resampled the airborne HSI to Sentinel-2A spectral and spatial characteristics and compared the temporal spectral variation for both image products using bottom of the atmosphere reflectance derived spectral vegetation indices. Thus, our overall objective was to identify key spectral features for assessing phenospectral dynamics (i.e. spectral changes as a function of vegetation phenological changes) for different vegetation physiognomies over a range of spectral, spatial and temporal scales at the Mer Bleue peatland. Furthermore, a novel aspect of our study is the evaluation of Sentinel-2A imagery for detecting phenological changes at the landscape level in a peatland area. More specifically, we addressed the following questions: 1: What are the main spectral features of the different vegetation physiognomies at the Mer Bleue peatland based on field spectroscopy? 2: How consistent are the spectral features of the different vegetation physiognomies at the Mer Bleue peatland when comparing resampled ground spectroscopy and airborne HSI? 3: How do ground reflectance and spectral indices at the Mer Bleue peatland compare between Sentinel-2A and airborne HSI? To the best of our knowledge, this is the first study that uses Sentinel-2A imagery in a northern peatland to assess seasonal phenological changes by integrating field spectroscopy and airborne HSI. This assessment is of great value for current and future land product validation efforts using satellite platforms.

2. Methods

2.1. Study area

This study was carried out at the Mer Bleue Conservation Area (MBCA) located east of the City of Ottawa, Ontario, Canada (Fig. 1). The MBCA is a 2800 ha ombrotrophic bog (i.e. water and nutrients come from precipitation and deposition as opposed to telluric sources) with hummock-hollow-lawn microtopographic features, poor fen sections, and beaver ponds around its margins (Moore et al., 2011). The climate of the region is cool continental, with a 30-year (1971–2000) mean annual temperature of 6.0 ± 0.8 °C. According to Roulet et al. (2007), the mean annual precipitation at Mer Bleue is 943 mm, of which approximately 235 mm falls as snow generally between December and March. In addition, the total precipitation is fairly evenly distributed throughout the year, with a minimum of 58 mm in February and a maximum of 90 mm in July.

The elevation for Mer Bleue is approximately 73 m ASL. The bog is slightly domed, with a peat depth increasing from 0.3 m along the edge to > 5 m across most of the area. Within the MBCA, the Mer Bleue Research Observatory (MBRO) is a long-term research site located in the northwest section (Fig. 1a). The MBRO covers approximately 10 ha and encompasses a series of boardwalks that allow for the implementation of field measurements of various types (e.g. gas exchange chambers, eddy covariance tower, field spectroscopy). For this study, we selected 5 vegetation physiognomic classes based on areas