BURN SEVERITY ASSESSMENT OF A HEATHLAND FIRE IN BELGIUM USING APEX HYPERSPECTRAL INDICES

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ABSTRACT

Heathland and peat bogs are highly valued as habitats for biodiversity conservation and as landscapes of European cultural heritage. In the past decades, significant efforts and resources have been invested to protect and manage remaining heathlands in order to conserve their intrinsic value. Uncontrolled large fires however are a major threat for the biodiversity of protected heathlands. One of the important factors influencing post-fire vegetation recovery is the severity of the fire. In forest ecosystems, remote sensing has been shown to be a useful tool to clarify the complex interaction between fires and severity. Heathland ecosystems have however received much less attention. In this study, we used indices derived from airborne Imaging Spectroscopy (IS) data to assess the burn severity of the major fire of May 25, 2011 in the *Kalmthoutse Heide* (Belgium). APEX imagery were acquired one month after the fire (June 27, 2011), and a modified version of the Composite Burn Index (CBI), targeted at heathland ecosystems, was developed to collect burn severity field reference data shortly after the fire. Field sample design was stratified, based on pre-fire dominant vegetation types: *Calluna vulgaris, Erica tetralix, Molinia caerulea* and *Pinus sylvestris*. We analysed the effect of pre-fire vegetation type on correlations between the modified CBI and several IS indices typically used for burn severity assessments. When correlating the modified CBI over all vegetation types together, correlation was low, with R^2 for the different indices ranging between 0.07 and 0.4. Taking pre-fire vegetation types into account however, correlation coefficients increased, with MIRBI demonstrating the best performance for *Molinia* and *Erica* (R^2 = 0.78 and 0.42, respectively). In *Calluna* and *Pinus* stands, CSI and NDVI achieved the highest correlations, with R^2 = 0.65 and 0.64 respectively. As such, this study showed the disparate performance of spectral indices to assess burn severity among different vegetation types, highlighting the advantage of a stratification per vegetation type to produce optimal burn severity maps.

INTRODUCTION

Heathlands are highly valued as habitats for biodiversity conservation, as relict landscapes of European heritage and as prime leisure areas (1,2,3). Most remaining heathlands are now protected under the European Habitats Directive (92/43/EEC), European Birds Directive (2009/147/EC) or under national legislation. Although prescribed burning is used as a management tool in many heathlands (2), uncontrolled wildfires are a major threat to heathland habitats (1). In the short-term, heath fires partially or completely remove the vegetation layer and litter. In the long-term, wildfires can alter species distributions (3). As a result, typical heathland species such as

Erica tetralix and *Calluna vulgaris* are replaced by dominant grasses like *Molinia caerulea*. Such degraded heathlands become even more vulnerable to wildfires as they produce large amounts of highly flammable dead grass material (4), thus risking to enter a self-enforcing cycle.

The severity of a fire is one of the factors controlling post-fire vegetation recovery and species composition (5). In the last decades, remote sensing techniques have emerged in wildfire studies (see (6) for a review) and various methods have been developed for assessing burn severity. Spectral indices (SIs) are the most widely used technique, due to their conceptual simplicity and computational efficiency (7). Many studies rely on the Normalized Difference Vegetation Index (NDVI) as a spectral index (3), which uses the absorption and reflection characteristics of plants in the R (red) and NIR (near-infrared) spectral regions respectively. Numerous modifications of the NDVI have been derived to reduce atmospheric sensitivity and background variability (7). Other spectral indices have been developed specifically to detect post-fire effects: the Burned Area Index (BAI, (8)), the Char Soil Index (CSI, (9)), the Mid Infrared Burn Index (MIRBI, (10)) and the Normalized Burn Ratio (NBR, (11)). Images are often used bi-temporally by differencing the post- and pre-fire index images, as this strongly reduces the spectral confusion between burned areas and spectrally similar terrain features like water, shadow and dark soil (7). One of these approaches, i.e. the dNBR (differenced Normalized Burn ratio), has become the standard spectral index approach to assess burn severity. However, the use of bi-temporal indices does not always produce better results (12). In addition, the bi-temporal approach is more data-demanding and hence constrained by e.g. limited availability of cloud-free imagery (3). Therefore, (3) among others emphasize the utility of mono-temporal images for burn severity assessments. Previous studies showed that burn severity assessments in forests generally achieve better results than in low cover environments such as shrublands or grasslands (11). Heath landscapes generally have characteristic sparse vegetation cover as well. So far, little is known about how conventional burn severity indices perform in these landscapes.

On May 25 2011, a wildfire destroyed large areas of the *Kalmthoutse Heide*, a protected heath landscape in Belgium. The fire event and imaging spectroscopy data availability provided a unique opportunity to evaluate the performance of existing burn severity indices in heathland ecosystems. Additionally, the availability of a pre-fire full coverage detailed vegetation map enabled us to evaluate the effect of the pre-fire vegetation type on the performance of the SIs.

METHODS

Study area

The *Kalmthoutse Heide* is a protected heathland landscape in Belgium, 25 km north of Antwerp at the border of the Netherlands. The 1000 ha core area consists of different heathland vegetation types. Wet heath, mainly *Erica tetralix*, is endangered by encroaching grass species, most importantly *Molinia caerulea*. Dry heath, dominated by *Calluna vulgaris* vegetation, is situated on more sandy soils. Sand dunes and acidic pools are scattered across the region. The inner heathland area is surrounded by coniferous woodlands (*Pinus* ssp.) and pastures. During exceptionally dry periods, mostly in late spring or summer, the area is prone to wildfires. The 2011 spring season was extremely dry and warm, causing fires in several reserves in Belgium. On May 25 and 26 2011, a wildfire destroyed more than 600 ha of the Kalmthoutse Heide, 440 ha of which was located in the core heathland area. This fire is the subject of our research.

Field Data

Field measurements were collected 10 to 12 weeks post-fire using a modified version of the Geometrically Structured Composite Burn Index (GeoCBI, 13). The GeoCBI is an adaptation of the Composite Burn Index (CBI, 11). The GeoCBI and CBI assess several factors of burn severity in the field for five vegetation strata: (i) substrates; (ii) grasses, herbs and small shrubs below 1m; (iii) tall shrubs and trees up to 5 m; (iv) trees 5 - 20 m and (v) big trees taller than 20 m. The GeoCBI differs from the CBI by including the fraction of cover (FCOV) of each vegetation layer and should therefore more closely reflect the spectral mixture as perceived by remote sensing systems. In heathland vegetation, shrubs rarely grow higher than 1 meter leaving only two strata to analyze. To account for the characteristics of heathland vegetation, we added and modified some factors according to field expert knowledge and literature review. The factor scores were rated between zero (unburned) and one (high severity) and averaged per stratum. A plot's final GeoCBI score was then calculated as the average stratum scores weighted by their FCOV.

In total, 109 field plots were measured. To study effects of pre-fire vegetation type on the GeoCBI – SI correlations, we stratified our sample design based on four vegetation types, derived from a 2007 vegetation map and verified with field notes: *Calluna vulgaris*-dominated heath (dry heath): 34 plots, *Erica tetralix*-dominated heath (wet heath): 29 plots, *Molinia caerulea* (invasive grasses): 27 plots and *Pinus* ssp. (coniferous woodland): 8 plots. Plots were located using a Real Time Kinematic Global Positioning System (RTK-GPS, Trimble GPS R6+, Trimble Navigation Limited, CA, USA). In each plot, the modified GeoCBI was recorded in circular plots of 4 m diameter, which approximates the 2.4 m image spatial resolution (see next paragraph).

Airborne hyperspectral APEX data

Airborne image data of the Kalmthoutse Heide were acquired on June 27, 2011, i.e. approximately one month post-fire, using the Airborne Prism Experiment (APEX) sensor. The sensor was operated by the Flemish Institute for Technological Research (VITO), and images were acquired with a spatial resolution of ~ 2.4 m. Spectrally, the data consisted of 288 narrow-band images, ranging from the visible to the longer shortwave infrared (LSWIR) spectral domain (410 to 2450 nm), with a spectral resolution between 5 and 10 nm (14). Geometric, radiometric and atmospheric correction were performed using VITO's in-house Central Data Processing Center (CDPC) (15). After these corrections, the obtained data product consisted of 288 bands of reflectance images. Bands within atmospheric water absorption regions (881-986 nm; 1072-1176 nm; 1322-1450 nm; 1790-1969 nm), were excluded from the analysis.

Ancillary data

The Kalmthoutse Heide has been the subject of a 5-year study (2007-2011) on heathland habitat quality mapping using imaging spectroscopy. This study provided us with a thoroughly validated vegetation map of June 2007 (16), on which we based the pre-fire vegetation stratification for the field sampling. Additionally, a detailed burn scar map was provided by VITO, which was produced using 0.25 cm spatial resolution, 4-band visible and infrared (VNIR) UltraCam imagery of June 2, 2011, i.e. five days after the fire event. This burn scar map was visually validated by local terrain managers.

Spectral Indices tested in the study

Table 1. Spectral indices tested in this study (B: Blue, R: Red, NIR: Near Infrared, SSWIR: Shorter Short Wave Infrared, LSWIR: Longer Short Wave Infrared). See text for the wavelength used for each region to calculate the indices.

Spectral index	Abbreviation	Formula
Normalized Difference Vegetation Index	NDVI	$\mathrm{NDVI} = \frac{\mathrm{NIR-R}}{\mathrm{NIR+R}}$
Global Environmental Monitoring Index	GEMI	$\mathrm{GEMI} = \gamma(1 - 0.25\,\gamma) - \frac{\mathrm{R}-0.125}{1-\mathrm{R}}$ with $\gamma = \frac{2(\mathrm{NIR}^2 - \mathrm{R}^2) + 1.5\,\mathrm{NIR} + 0.5\,\mathrm{R}}{\mathrm{NIR+R}+0.5}$
Enhanced Vegetation Index	EVI	$\mathrm{EVI} = 2.5\,\frac{\mathrm{NIR-R}}{\mathrm{NIR}-6\,\mathrm{R}-7.5\,\mathrm{B}+1}$
Soil Adjusted Vegetation Index	SAVI	$\mathrm{SAVI} = (1+\mathrm{L})\,\frac{\mathrm{NIR-R}}{\mathrm{NIR+R+L}}$ with $\mathrm{L} = 0.5$
Modified Soil Adjusted Vegetation Index	MSAVI	$\mathrm{MSAVI} = \frac{2\,\mathrm{NIR}+1-\sqrt{(2\,\mathrm{NIR}+1)^2 - 8\,(\mathrm{NIR-R})}}{2}$

Burned Area Index	BAI	$\mathrm{BAI} = \frac{1}{(0.1+\mathrm{R})^2 + (0.06+\mathrm{NIR})^2}$
Normalized Burn Ratio	NBR	$\mathrm{NBR} = \frac{\mathrm{NIR}-\mathrm{LSWIR}}{\mathrm{NIR}+\mathrm{LSWIR}}$
Char Soil Index	CSI	$\mathrm{CSI} = \frac{\mathrm{NIR}}{\mathrm{LSWIR}}$
Mid-Infrared Burn Index	MIRBI	$\mathrm{MIRBI} = 10\ \mathrm{LSWIR} - 9.8\ \mathrm{SSWIR} + 2$

The indices were calculated using the bands with following central wavelengths for each spectral region: B: 499 nm; G: 552 nm; R: 699 nm; NIR: 801 nm; SSWIR: 1302 nm; LSWIR: 2332 nm.

Relationship between SIs and burn severity (modified GeoCBI)

A linear regression analysis was applied between the SIs and the modified GeoCBI for each of the field plots. The correlation is defined by the coefficient of determination (R^2) which represents the proportion of total variance in burn severity that is explained by the SI, and statistical significance was quantified by the p-value using the F-statistic. Previous research demonstrated that the performance of spectral indices may depend on the pre-fire vegetation type (17). We performed our analysis per vegetation type as well as for the pooled dataset. Finally, a burn severity map was produced using the optimal parameters for each of the four vegetation types. For areas not falling in one of the four vegetation types, the best performing SI with the pooled dataset was used.

RESULTS

The correlation analysis of the data pooled together over all vegetation types resulted in poor correlations between the modified GeoCBI and SIs. Correlation per vegetation type however clearly showed stronger relationships (Table 2). The MSAVI and MIRBI explained most of the variance for the pooled data, with an R^2 of 0.40 for both indices. By stratifying the data per vegetation type, the correlations clearly increased. *Calluna* had the highest correlation with the CSI (R^2 = 0.65). Also the MIRBI and NBR were suitable in *Calluna* stands (R^2 = 0.40 and 0.55). In *Erica* species, the correlations remained relatively low, however, MIRBI revealed the highest correlation coefficient (R^2 = 0.42), followed by the NDVI (R^2 = 0.38). Relatively high correlations were obtained for *Molinia* vegetation with MIRBI having the highest R^2 value (0.78). The GeoCBI of *Pinus* stands revealed strong relationships with indices that generally performed poorer in other vegetation types: the NDVI, SAVI and GEMI had the strongest correlations of 0.64, 0.63 and 0.59 respectively.

*Table 2. Determination coefficient (R^2) for the spectral indices (see Table 1) with pooled data and data per vegetation type (n: number of field plots; *** $p < 0.0001$; ** $p < 0.001$; * $p < 0.05$; no asterisk: $p > 0.05$; values higher than 0.35 are given in bold).*

R^2	**Pooled data (n = 109)**	**Per vegetation type**			
		***Calluna* (n=34)**	***Erica* (n = 29)**	***Molinia* (n = 27)**	***Pinus* (n = 8)**
NDVI	0.14***	**0.49*** **	**0.38*** **	0.15*	**0.64***
GEMI	0.21***	**0.45*** **	0.15*	**0.45*** **	**0.59***
EVI	0.07**	0.33***	0.14*	**0.60*** **	**0.44**
SAVI	0.24***	**0.50*** **	0.22**	**0.40*** **	**0.63***
MSAVI	**0.40*** **	**0.41*** **	0.13	**0.55*** **	**0.54***
BAI	0.26***	0.32***	0.10	0.31**	**0.39**
NBR	0.22***	**0.55*** **	0.25**	**0.38*** **	0.33
CSI	0.18***	**0.65*** **	0.26**	**0.57*** **	**0.50**
MIRBI	**0.40*** **	**0.58*** **	**0.42*** **	**0.78*** **	0.19

Figure 1 demonstrates that the relationship between the MIRBI and the modified GeoCBI clearly differed among the different vegetation types. As a consequence, the relationship observed for the pooled dataset strongly generalizes and does not capture vegetation type-specific trends.

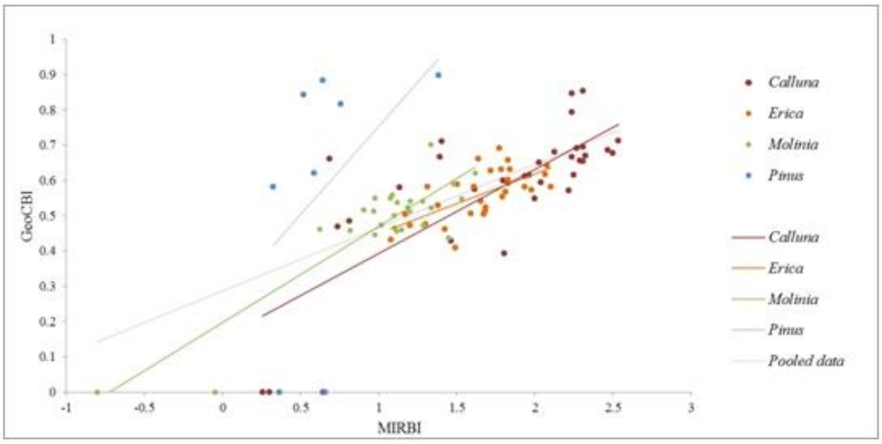

Figure 1. Scatter plots and linear regression lines between the Mid-Infrared Burn Index (MIRBI) and the Geometrically structured Composite Burn Index (GeoCBI) field data, for pooled data and data per vegetation type.

CONCLUSIONS

The results presented in this paper indicate the potential of using imaging spectroscopy indices for assessing burn severity in heathland landscapes, in a similar way as in forest areas. Using a single SI for all vegetation types within a heathland however is undesirable, as higher correlations between SIs and field data are obtained, when separate SIs are used per pre-fire vegetation type. This study is one of the few ever performed in heathland habitats, and more research is needed to further validate our findings across different heathland fires.

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