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WILDFIRE MONITORING WITH REMOTE SENSING: HYPERSPECTRAL TECNIQUES FOR UPLAND LANDSCAPES

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Summary

Introduction

Biomass burning affects the land and atmosphere through the combustion of vegetation and organic soils and transfers large amounts of chemical constituents directly into the troposphere. Understanding the impact of global biomass burning on the terrestrial biosphere, atmosphere, and the impact over time are major scientific questions [Wooster et al., 2013].

At the local scale, fires are a major security hazard in numerous countries around the world, adversely affecting vegetated resources and human communities. In Europe, Mediterranean countries are the most affected by vegetation fires, with an average of almost 50,000 fires between 1980 and 2008 and an estimated total cost around 1% of Domestic Product [Santin and Doerr, 2016] including the cost of firefighting organizations, fire insurance administration, and protection to buildings [Sobrino et al., 2013]. Italy is one of the Mediterranean countries which every year is dramatically affected by forest fire. In the period January-August 2014, 2,653 forest fires were registered, affecting 8,729 hectares [JRC, 2012] (Figure 1). Scientific and government communities are actively involved in prevention, crisis management and post fire recovery by using different kind of tools. For example, specialised airborne (Canadair) for retardant release are used for fire suppression, whilst satellite remote sensing at coarse resolution (e.g. MODIS) are used for detection and monitoring on large scale. [http://effis.jrc.ec.europa.eu/applications/fire-news].

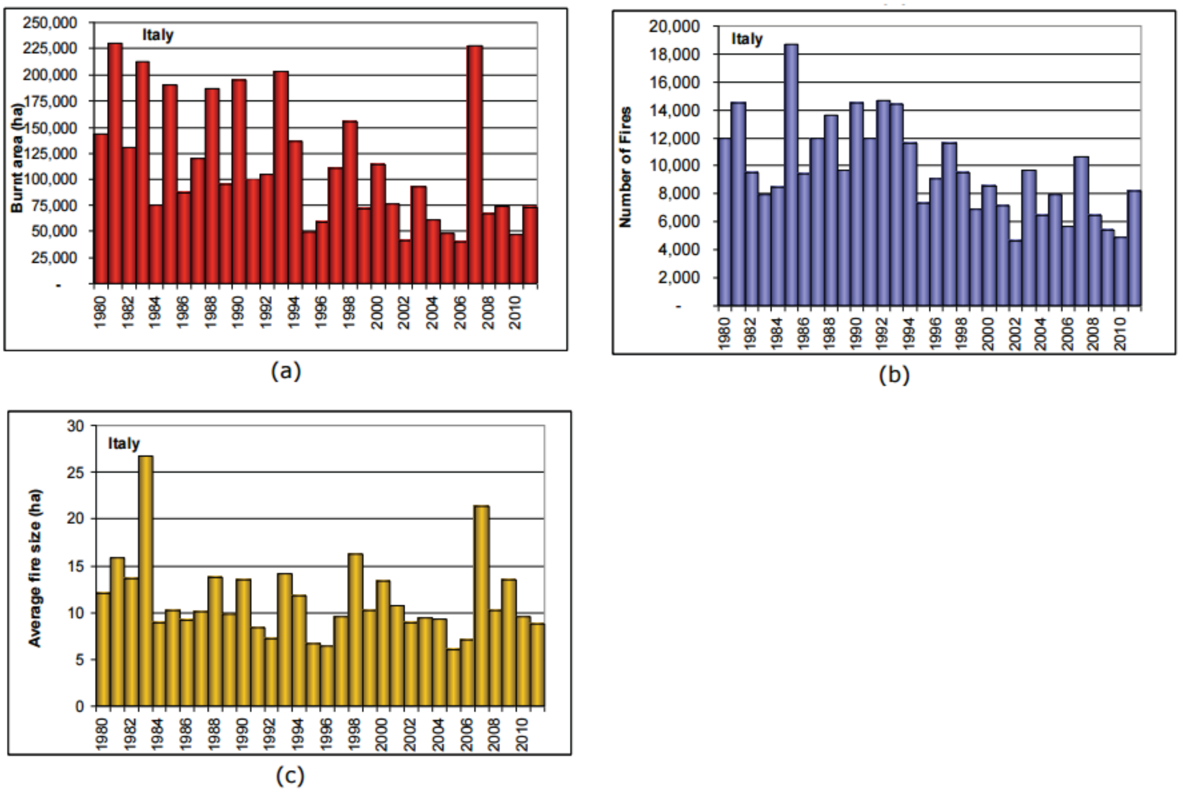

Figure 1. Trends in satellite-detected vegetation fires in Italy from 1980 to 2011: (a) number of fires; (b) burned area and; (c) average fire size [source, JRC 2012, p.82].

Northern European countries are experiencing an increasing number of uncontrolled vegetation fires when more frequent "exceptional" drought seasons occur. The timing and magnitude of the fire weather peak varies within and between seasons for the United Kingdom (UK), with 2011 being a year with periods of high Fire Weather Index (FWI) (Figure 2). The number of vegetation fires attended by Fire and Rescue services in Great Britain (England, Scotland, and Wales) parallels this trend (Figure 3). Further information on vegetation fire trends and the significance of 2011 on UK wildfire policy is analysed in Gazzard et al. [2016].

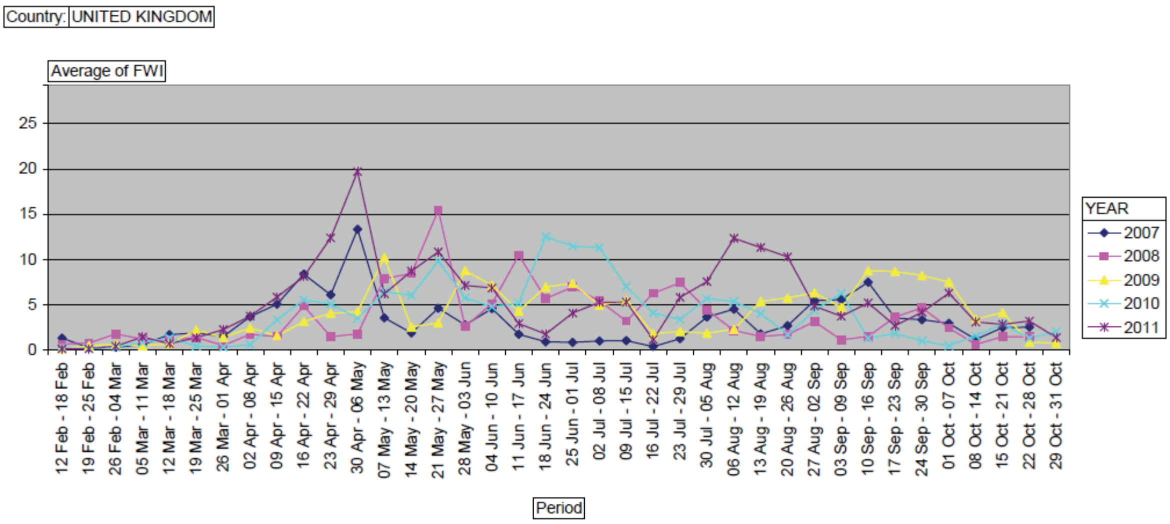

Figure 2. Weekly average Fire Weather Index (FWI) for the UK, 2007 to 2011, showing high fire risk in spring and slightly lower peak in late summer 2011. Note the variability in timing and magnitude of the FWI peaks from year to year. Source: JRC [2012].

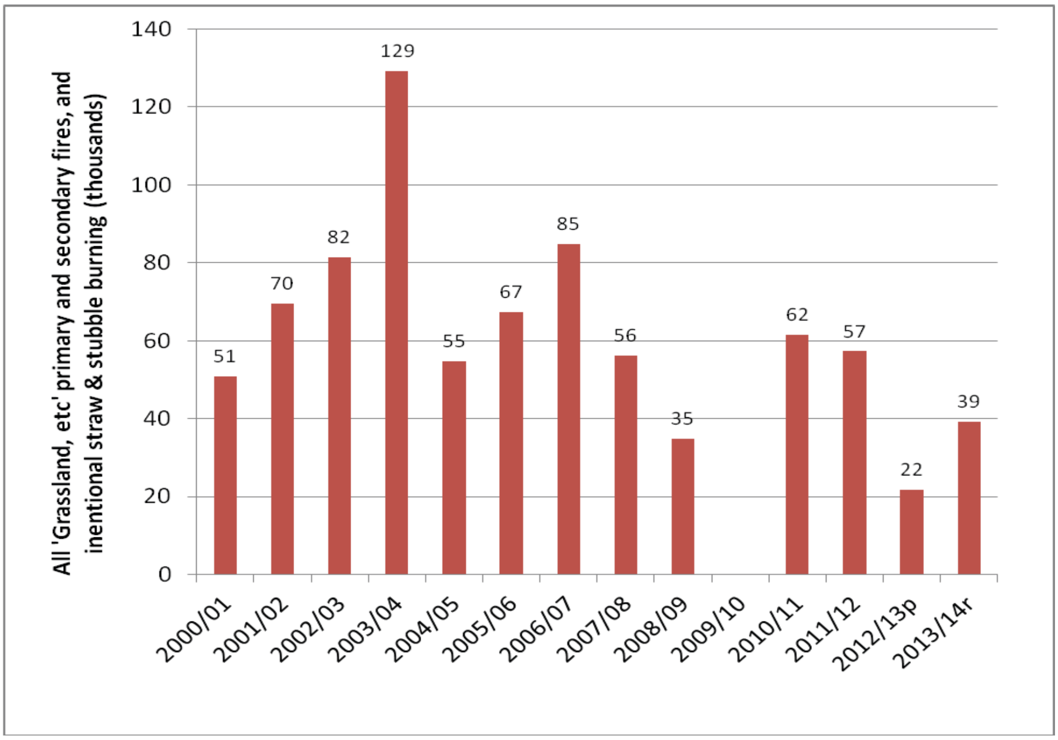

Figure 3. Total number of vegetation fires attended by Fire and Rescue Services in Great Britain (England, Wales and Scotland) for financial years 2000/01 to 2013/14 as recorded in the Department for Communities and Local Government (DCLG) Incident Recording System. A financial year runs from 1 April to 31 March, often splitting the spring fire season. Vegetation fires includes all 'Grassland, crops, woods, etc.' primary fires, all 'Grassland, heathland, etc.' secondary fires and 'Intentional straw & stubble burning'. Data and definitions as specified in Table 1c of DCLG [2015].

Fire has also been used over the centuries to manage ecosystems. Prescribed fires deliberately disturb the natural vegetation succession with the goal of promoting new vegetation growth (e.g. for grazing livestock or game management [e.g. Yallop et al., 2009] or reducing biomass loads. Whilst there are benefits to using prescribed fire, there are also negative effects of fire on the landscape including: enhanced soil erosion, carbon loss and transformation of ecosystems [Santín and Doerr, 2016]. Therefore, there can often be trade-offs between the positive and negative effects of fire, and between multiple users of the landscape depending on the environmental, conservation, social or economic state desired. For example, in the UK many areas of the upland peatlands and moorlands are managed by rotational prescribed burning for game birds, but in recent years there has been a growing body of research investigating the wider ecosystem services benefits and disbenefits of this management practice, often leading to disagreement and debate between different stakeholders (for further discussion of these debates see Davies et al. [2016a; 2016b]).

Due to the scale and dynamics of the phenomena, remote sensing from space has been shown to be adequate for fire detection, characterization and impact assessment. Cloud cover poses severe limitations on the use of optical data, especially in the UK, but radar shows promise for burn scar detection and monitoring [Millin-Chalabi et al., 2014]. Other limitations of satellite sensors are low spatial resolution (e.g. MODIS, 1 km) and low temporal resolution (e.g. Landsat 8, 16 days). Improved detection algorithms now allow airborne detection of smaller fires that may be important precursors of larger burns, and tracking of fire growth when incorporated into operational fire spread models [Smith et al., 2005].

Imaging spectroscopy based on hyperspectral data theoretically allows all stages of the fire cycle to be assessed, from the degree of "fire proneness" for fire prevention, through to characterising the burning phase, and post-fire burn severity assessment. Until now, the use of hyperpectral techniques has been limited by the cost and weight of the airborne instruments and having only one operational satellite (Eo1-Hyperion), which has limited acquisition opportunities in high latitude countries such as the UK. There is renewed interest in imaging spectroscopy for fire applications due to new hyperspectral satellite missions (EnMap and PRISMA) and the development of light and relatively cheap instruments, including hyperspectral sensors linked to the expansion of the unmanned aerial vehicles (UAV) market. Both, in theory, offer the possibility to characterise fires in northern European countries such as UK.

1. Scientific background

1.1 K-line emission peak method

Vegetation fire emits heat so thermal remote sensing is suitable to its identification and study. Trace elements such as potassium (K) present in biomass have low excitation energy and can be ionized at temperatures occurring during flaming combustion [Vodacek, 2002; Amici et al., 2011]. This produces a sudden increase in reflectance at 766.5 nm and 769.9 nm for K. Detaiiled technical information can be found in [Vodacek, 2002; Amici et al., 2011]. This sharp peak or emission line can be detected by very narrow band (hyperspectral) sensors such as an Analytical Spectral Devices, Inc. FieldSpec FR field spectroradiometer [ASD, 2017]. As K emission is specific to flaming vegetation combustion, it could allow flames to be detected and therefore the separation of smouldering from flaming vegetation combustion during active fires.

We would expect to measure distinct K-emission peaks for wet and dry vegetation, though not for peat which does not easily produce flames. In contrast, combustion in peat tends to be smouldering rather than flaming, due in part to a high moisture content [Rein et al., 2008]. This could potentially contribute to spatially-explicit estimates of the two different phases of combustion over peat moorlands.

1.2 Aim

The aim of the experiment was to investigate whether the flaming and smouldering combustion stages of typical moorland vegetation and peat samples could be identified using the K-line emission peak method recorded using a field spectroradiometer.

2. Method

2.1 Reflectance measurement

Reflectance measurements were carried out at the University of Salford campus using an ASD FieldSpec FR spectroradiometer (sampling parameters in Table 1) to measure different types of organic matter including vegetation and peat soil. Figure 4 shows the acquisition set-up of the Fieldspec FR and VIS-TIR camera. The spectral measurements were made under direct sunlight and relative to a white calibrated Spectralon panel panel (LabSphere 99% diffuse reflectance panel). The spectral data were post-processed to absolute reflectance. The measurements were taken between 15:00 – 16:30 BST (14:00-15:30 GMT). ASD reflectance spectra of the samples were collected before, during and after the flaming combustion phase. A total of 70 reflectance spectra were acquired. The 8 degrees foreoptics was chosen as optimal for pre-fire sample measurements due to the limited size of available samples. For the burning experiment, the samples were placed in aluminium trays about 1.3 m distance from the fiber optics. This was found to be a safe distance for the instrument, although we were expecting some aluminium effect on the spectrum. Ideally, we would have liked to measure burning spectra with 1 degree foreoptic, however, this was not available at the time, so a good compromise was reached by using the 8 degrees one.

Parameter	**Settings**
Spectral range	350-2500 nm
Spectral resolution	3 nm @ 700 nm 10 nm @ 1400/2100 nm
Spectral sampling (bandwidth)	1.4 nm @ 350-1000 nm 1.1 nm @ 1001-2500 nm
Wavelength accuracy	0.5 nm
Scanning time	100 milliseconds
Channels	2151
Input	1.5 m fibre optic cable
Foreoptic	8 degree FOV lens
	VNIR detector (350-1000 nm) SWIR 1 detector (1001-1800 nm) SWIR 2 detector (1801-2500 nm)
Calibration	Calibrated white Spectralon panel

Table 1. Measurement characteristics of ASD FieldSpec FR spectroradiometer [Source: ASD Inc, 2017].

Figure 4. ASD Fieldspec FR (A) carried on back of operator, with the sensor head (B) and moveable white calibration panel (C) attached to a vertical pole. The TIR-VIS camera (D) is mounted on the tripod behind.

2.2 Thermal camera

A FLIR i5 spot thermal camera was used to capture the thermal infrared signature of the fires. The default emissivity (ε) value of 0.95 was used, which is within the range of many vegetation species [e.g. Jones and Vaughan, 2010; Rubio et al., 1997]. However, the upper limit of the camera was only ~ 240°C, and could not capture the full temperature range experienced by the samples. Therefore, Figure 5 shows highly saturated images. Further post-processing of the samples was not carried out. For future studies, more appropriate cameras with video recording capabilities, high resolution images and temperature ranges over 1000°C (such as handheld FLIR T-600 series), should be used.

Figure 5. (a) Smouldering grass; (b) FLIR i5 thermal infrared image taken at the same time.

2.3 Samples

The vegetation species selected were typical of upland and moorland areas in the UK (Moors for the Future Partnership, no date). These included: live heather (*Calluna vulgaris*); dry heather; dried cotton grass (*Eriophorum spp.*); dry moss; and dry gorse (*Ulex spp.*). We also burnt a sample of air-dried upland peat.

a) Common heather (Calluna vulgaris) sample

- Low-growing perennial shrub generally 20-60cm tall, but sometimes much shorter.
- The dominant plant in most heathland and moorland in Europe, and in some bog vegetation.
- Small scale-like leaves (less than 2–3mm long), borne in opposite and crossing pairs.
- Flowers emerge in late summer; in wild plants these are normally mauve (and occasionally white).
- Common heather seed is applied as part of the Moors for the Future Partnership's "brash works" and aerial seed application programme which is helping to stabilise and restore large areas of damaged moorland.

b) Cotton grass (Eriophorum spp.)

- Both common cotton grass (*E. angustifolium*) and hare's-tail cotton grass (*E. vaginatum*) likely present.
- Shoots can grow between 20-50cm.
- Inflorescence characterised by a fluffy white ball.
- Relevant for its ability to stabilise peat.

c) General moss *(Bryophytes*)

- Shoots can grow typically 0.2–10 cm with some species up 50cm.
- Stems may be simple or branched and upright or prostrate.

d) *European gorse (Ulex europaeus) sample)*

- An extremely spiny, evergreen shrub which can grow to 2m in height.
- May form dense stands.
- Bright yellow, coconut scented flowers (December-July).

e) Peat

- Taken from within the Upper North Grain catchment in the Peak District National Park, UK; for details of the catchment see Clay and Evans (in press) and Goulsbra et al. [2014].
- Air dried for several days prior to analysis.

2.4 Weather conditions

Weather conditions for reflectance measurements in Manchester area were quite challenging as sun and intermittent cloud alternated (Table 2). A white reference calibration panel was therefore used for every set of measurements and 10 spectra were averaged for each sample.

Time	Temp (°C)	Weather	Wind (mph)	Humidity (%)	Atmospheric pressure (mbar)
14:50	15	Scattered clouds	12	59	1025
15:20	15	Scattered clouds	12	59	1025
15:50	14	Passing clouds	10	63	1025
16:20	14	Passing clouds	10	63	1025

Table 2. Weather conditions in Manchester during the experiment [Data from CustomWeather, 2015].

3. Results and initial analysis

3.1 Pre-fire spectra

A relative reduction in chlorophyll and retention of carotenoids during senescence is displayed as an increase in reflectance between 550 nm and 740 nm and a decrease in reflectance in 400 nm – 500 nm, respectively. Furthermore during senescence, the remaining materials in the plants are cellulose-lignin which shows a typical wide feature between 1900-2100 nm [Smith, 2005]. Figure 6 shows reflectance spectra measured in laboratory of magnolia grandiflora in both healthy and senescent condition.

Chorophyll-a absorption at approx 430 nm (blue) and at 640 nm (red) are highlighted with a green bracket [Curran P.J 1989]. The red bracket highlights the red edge (650-750 nm) which is distinctive of photosynthetic vegetation activity. The wide absorption feature centred at 2100 nm is due to the presence of cellulose and lignin in the plants [Smith et al., 2005].

Figure 7 shows a selection of representative reflectance spectra for peat and moorland vegetation measured before burning. Moorland vegetation *in situ* would be expected to show chlorophyll absorption features in the blue and red visible at 430 and 660 nm, respectively. The 660 nm absorption feature is minimal or absent because the samples were in a semi-dry condition which has produced a response similar to the onset of senescence. The raised red reflectance of the heather sample (Figure 7b) is also due to presence of mauve/purple flowers. The noise at the 1400 and 1940 nm water absorption features in all the spectra is due to residual moisture content.

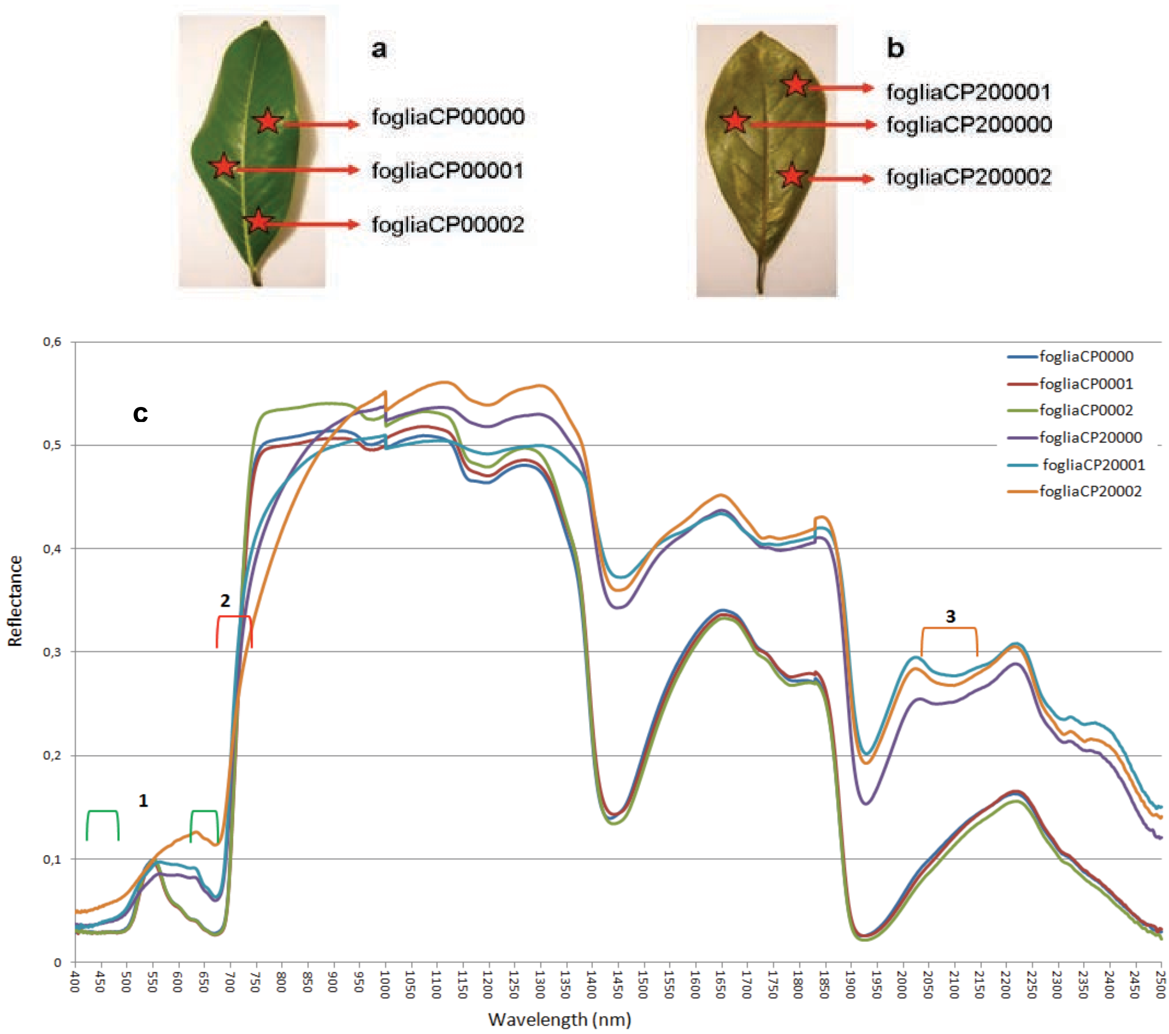

Figure 6. Magnolia grandiflora (a) green and (b) senescent leaves. Red stars indicate location where the spectra (c), have been recorded. 1) green brackets indicate the blue and red chlorophyll absorption features at 430 and 660 nm; 2) red bracket indicates the red edge and 3) orange bracket indicates lignin-cellulose centred on 2100 nm. Spectra from Masters school practicals at UNIMORE in 2012.

3.2 Combustion phase spectra

The reflectance spectra acquired during the combustion phase are shown in Figure 8. The smouldering peat spectra does not show a K emission line (Figure 8a), but the flaming vegetation spectra show a clear K emission peak (Figure 8b-e). The K emission line consists of two peaks, both in the visible spectral range, at 766.5 nm and 769.9 nm, alongside the 762 nm O_2 absorption band. Grass and heather produced relatively small flame lengths, whilst moss and gorse produced larger flames. Consequently, the K emission line is smaller for grass and heather (Figure 8b & 8c) compared the larger peaks for moss and gorse (Figure 9d & 9e). Higher fire intensity in gorse is due to the presence of flammable oils and the relatively high proportion of fine fuel from its needle-like leaves [Murgatroyd, 2002].

Conclusion

Reflectance spectra of moorland vegetation types have been measured in open air conditions before and during combustion. We noticed that different vegetation types in similar meteorological conditions (e.g. humidity), can produce a range of flame intensity. However, Fuel Moisture Content and the relative humidity of the air were not measured and should be included in any future work. The effect of peat humification, moisture content [McMorrow et al. 2005] and other biophysical properties on the intensity of flaming combustion in peat should also be investigated.

Peat sample combustion did not produce any flames and therefore no K emission line. In contrast, moorland vegetation showed a clear K emission line. The pre-burning spectra represent an initial dataset to be included in the vegetation spectral library under development at the University of Salford. The spectra acquired can potentially be used as end members to identify dry or semi-senescence species in hyperspectral satellite imagery. Although the thermal data have not been used, further experiments should use a TIR camera with appropriate specifications to help link peak intensity to flame temperature

Further work with ASD spectra is recommended to investigate the sensitivity of K-line detection to spectral resolution and identify a critical upper threshold. Operationally, new satellite sensors such as PRISMA, EnMap and HSUI which will be operating from 2018 will offer an opportunity to locate active fire fronts and to study burned area at medium resolution (30m/pix) even in countries such as UK where weather condition are not very favourable to VIS-NIR spectral range observation. With further work, there is potential for high spectral resolution VNIR sensors to be able to locate the flaming front of moorland fires using the K-line emission technique.

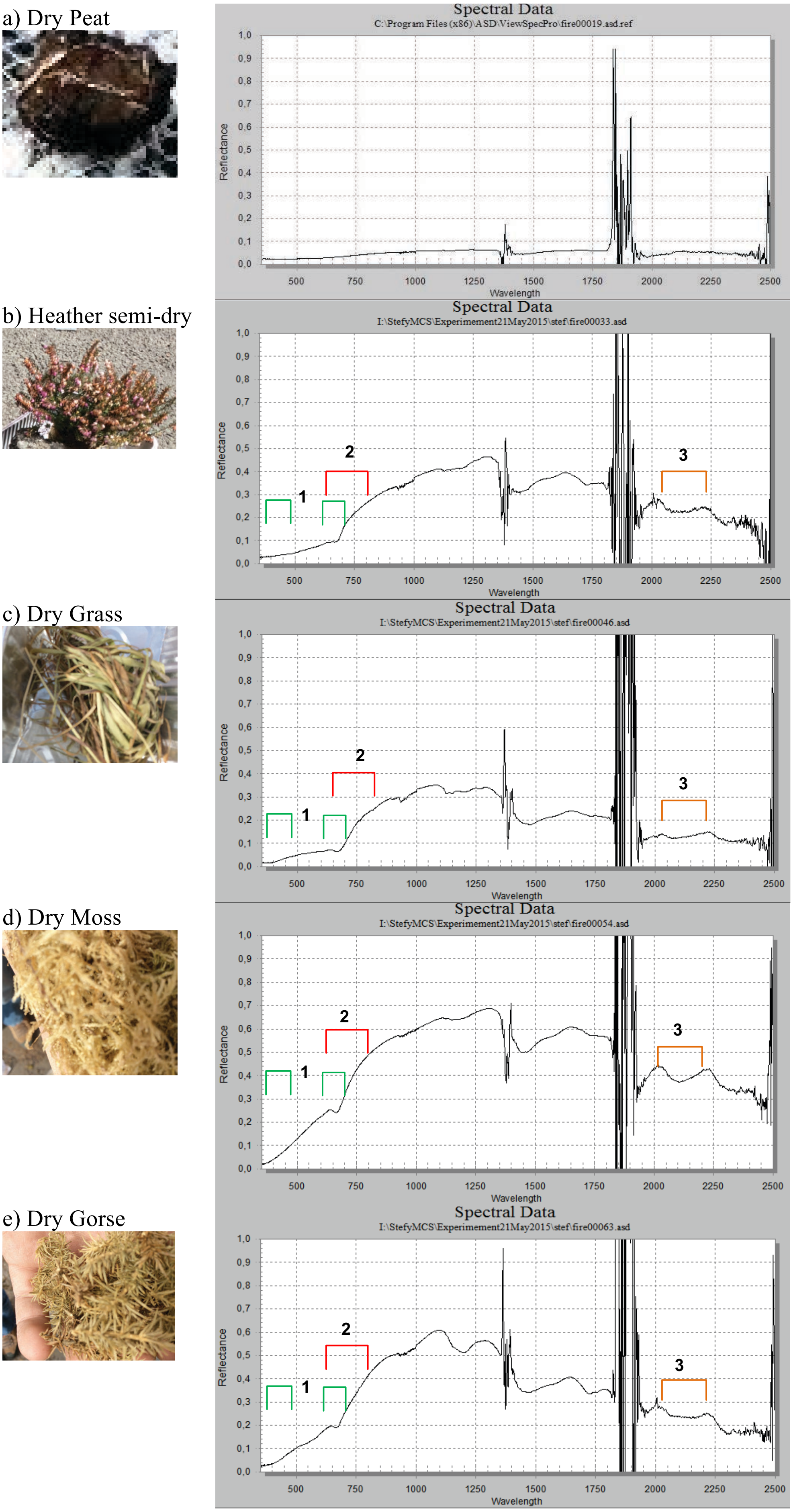

Figure 7. Peat reflectance spectrum and four species of moorland vegetation. (1) Chlorophyll absorption features at around 430 and 660 nm in green brackets; (2) red edge 680-750 nm in red brackets; and (3) cellulose-lignin absorption feature centred on 2100 nm in orange brackets.

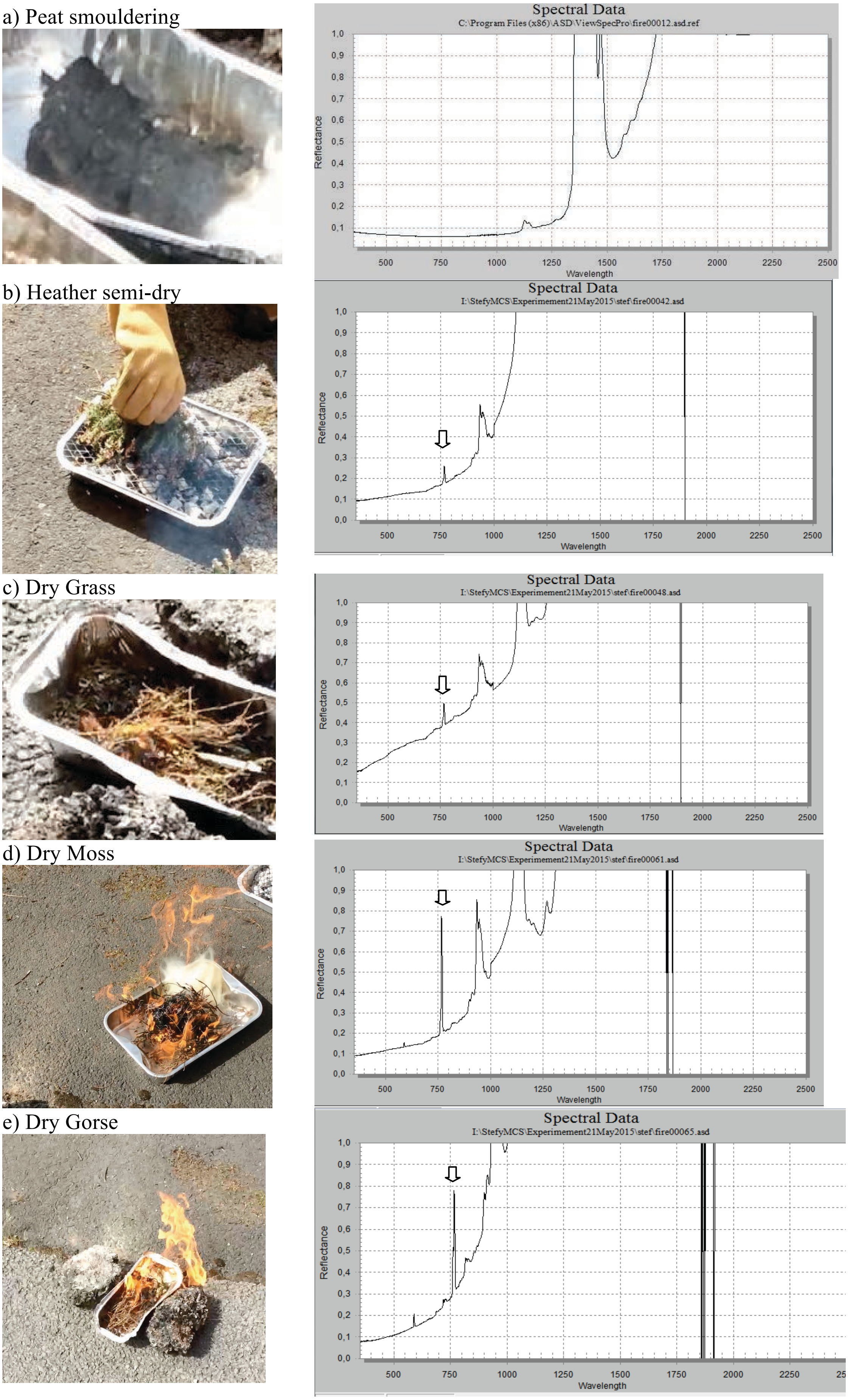

Figure 8. Smouldering peat reflectance spectrum and four types of moorland vegetation. K emission line present in flaming combustion spectra, b – e.

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