DETECTING SUB-SURFACE SOIL DISTURBANCE USING HYPERSPECTRAL FIRST DERIVATIVE BAND RATIOS OF ASSOCIATED VEGETATION STRESS

D. C. White [a, *], M. Williams [a], S. L. Barr [a]

[a] School of Civil Engineering & Geosciences, Newcastle University, UK – davina_cherie@yahoo.com

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ABSTRACT:

Previous studies conducted under controlled laboratory and controlled field conditions have demonstrated the ability of hyperspectral techniques to detect vegetation stress associated with elevated levels of soil gas and associated soil oxygen depletion. This paper investigates the capability and transferability of these hyperspectral techniques, in particular the Smith et al. (2004) 725:702 *nm* ratio, to identify vegetation stress features associated with sub-soil disturbance resulting from gas pipeline earthworks under heterogeneous field conditions. Field spectroradiometry data of barley were acquired in 2005 and 2006 at selected transects perpendicular to a stretch of buried gas pipeline in Aberdeenshire. Spectral reflectance and absorption features in the VIS-NIR are evaluated through first derivate analysis to establish their position, shape and magnitude and used to determine narrow waveband ratios which are tightly coupled to changes in photosynthetic function resulting from vegetation stress. First derivative ratios, 723:700 and 725:702 *nm*, detected vegetation stress above the gas pipeline where soil had been disturbed and were the same order of magnitude for the 2005 and 2006 data. Ratio values were similar to those conducted under controlled conditions by Smith et al. (2004), with differences of up to 56 % for spring barley between locations of soil disturbance and locations away from the pipeline, R^2 accounting for up to 62 % of the variance in the ratios of the regression. Student's T-tests revealed that the ratios were statistically significantly different between stress and no known stress within zones of soil disturbance at the 0.05 confidence level.

1. INTRODUCTION

Remediation involves the reinstatement of the land, flora, and other land use, where the sub-surface soil has been disturbed, as close as possible to its original condition. Sub-surface soil disturbance associated with gas pipeline earthworks can have an impact on adjacent land potentially resulting in drainage misalignment and collapse, sub-soil compaction (Pers. Comm. Donal Cullen, Bruce Mackie and Gerald Banks), and mixing of surface and subsurface horizons. These impacts can lead to changes in organic matter, clay, pH, aeration, water retention and nutrition (De Jong and Button, 1973; Rimmer, 1991). Vegetation stress associated with sub-surface soil disturbance has been observed as visual symptoms of chlorosis, stunted growth and sparse vegetation cover. To date research evaluating the health of vegetation overlying gas pipelines has been confined primarily to controlled laboratory and controlled field test sites, such as Smith et al. (2004), Noomen et al. (2006), and van der Meijde et al. (2006). These studies have demonstrated the capability of hyperspectral techniques (first derivative analysis, band ratios and continuum removal) to detect vegetation stress intimated to be a generic response to soil oxygen depletion resulting from elevated levels of soil gas. Smith et al. (2004) also suggested that their first derivative 725:702 *nm* ratio could be employed to detect other forms of soil oxygen depletion, such as sub-soil compaction and waterlogging, which can result from pipeline earthworks.

Hyperspectral remote sensing has the potential to provide a solution for detection and monitoring of pipeline earthworks associated sub-surface soil disturbance which can be inferred from resultant surface vegetation stress features. A key capability of hyperspectral data are their near contiguous narrow spectral wavebands which lend to first derivative analysis providing a more robust approach (much less affected by extraneous variables, such as partial plant cover under stress conditions) than broad band vegetation indices such as NDVI. Hyperspectral remote sensing is also potentially capable of providing more rigorous, reliable and repeatable detection and monitoring than current visual inspections from aircraft overflights. Visual inspections can be unreliable at identifying stress due to human subjectivity, and are personnel and time intensive (Hausamann et al., 2003; Zirnig et al., 2002).

The aim of this paper is to determine the capability of hyperspectral field spectroradiometry data to identify surface vegetation stress features associated with sub-surface soil disturbance resulting from gas pipeline earthworks under heterogeneous field conditions. Spectral reflectance and absorption features in the VIS-NIR are evaluated through first derivate analysis to establish their position, shape and magnitude. These first derivative VIS-NIR features are used to identify which narrow waveband ratios are tightly coupled to changes in photosynthetic function resulting from vegetation stress, in particular the Smith et al. (2004) ratio.

2. FIELD METHODS AND DATA ANALYSIS

2.1 Study site

The study area consists of a 9 km stretch of 508 mm buried Natural Gas Liquids (NGL) pipeline in Aberdeenshire, Scotland, installed and remediated in 1983. A second 457 mm gas pipeline is also present within the same corridor and was installed in 1980 (Figure 1). Land use is predominantly arable crops (barley, wheat and oats) with some grassland. The

* Corresponding author.

pipeline is routed through a mixed sub-soil, textures ranging from *other mineral soils* with *sandy loam* in places, *sandy soil* which may have a *sandy loam* top-soil, and *sand*.

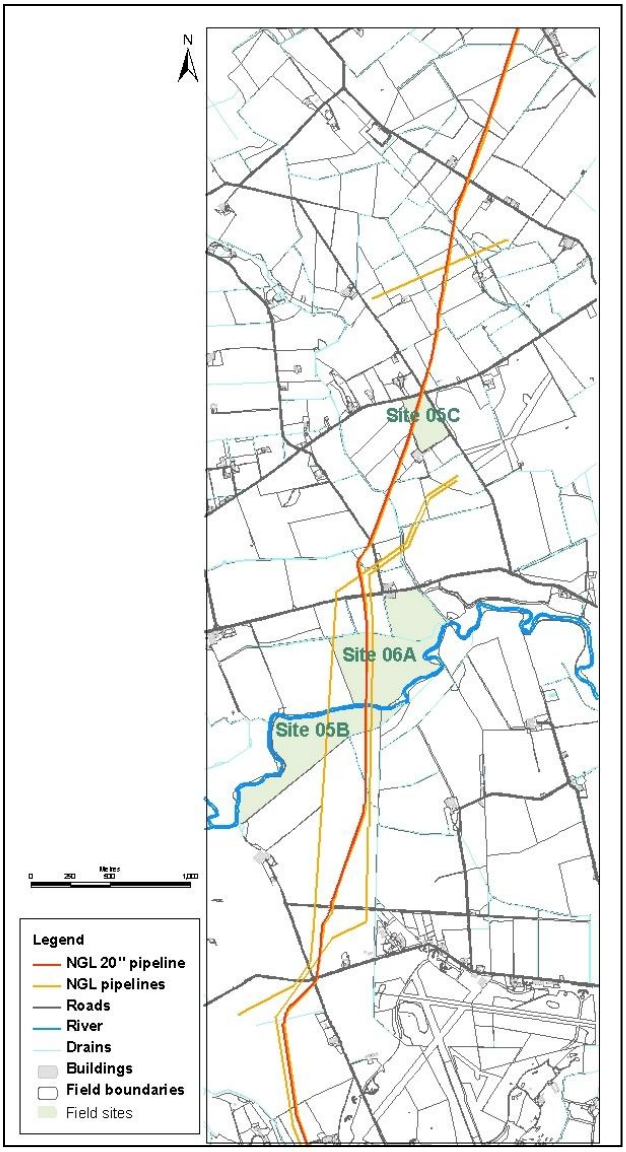


Figure 1. Map of study area with location of test sites 05B, 05C and 06A annotated.

2.2 Field spectroradiometry acquisition

Field spectroradiometry data of barley were acquired for two field campaigns in 2005 and 2006 at selected transects perpendicular to a stretch of buried gas pipeline in Aberdeenshire. A spatially intensive field spectroradiometry experimental design for acquiring spectra under challenging heterogeneous field conditions was developed and implemented. The sampling strategy used in 2005 was refined for the 2006 campaign (see results and discussion section). The experimental transect sampling design used in the 2006 field campaign consisted of transects extending 70 m either side of the 508 mm gas pipeline to encapsulate the full spatial signature of vegetation stress features, zones of known soil disturbance, and zones with no known soil disturbance (Figure 2). This enabled associations between soil properties measured and vegetation stress to be investigated. The extent of the transects was also determined by the practicalities of field spectroradiometry. Two transects were acquired at each test site above the 508 mm pipeline, one above an identified stress site and the other at a control site with no visible stress (Figure 2). The rigour and success of the experimental design is determined by the ability of the first derivative ratios evaluated to detect pipeline earthworks associated sub-surface soil disturbance from resultant surface vegetation stress.

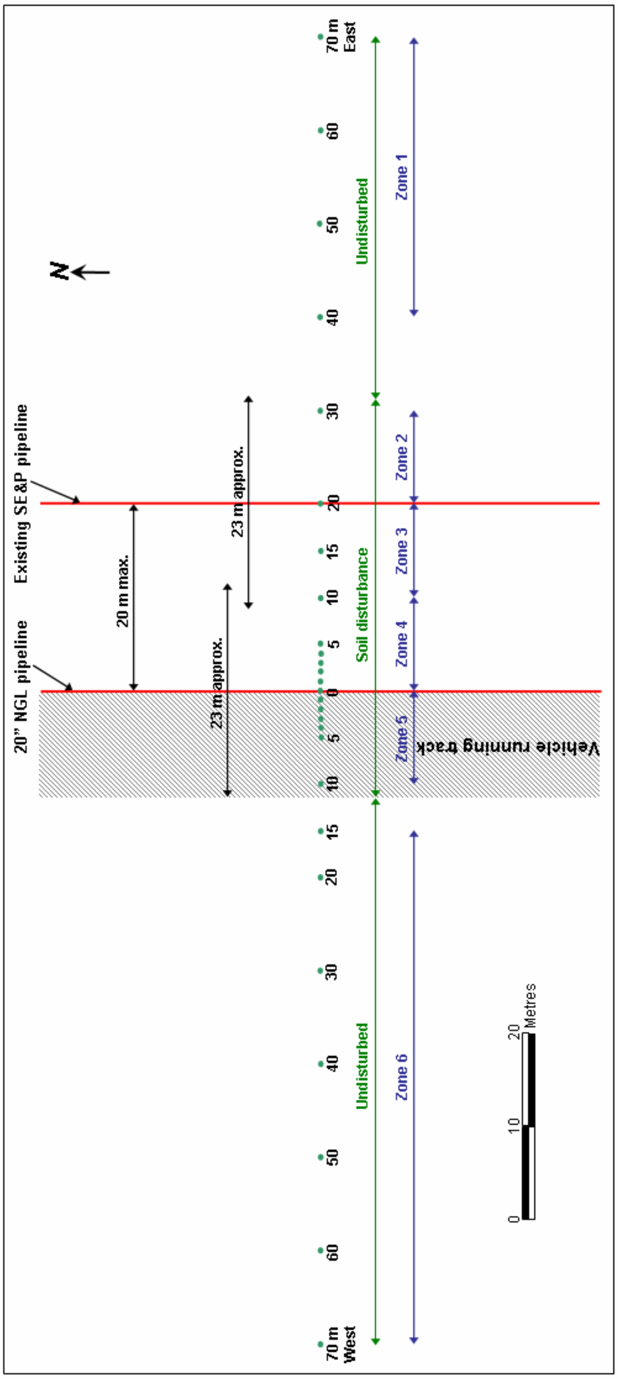


Figure 2. Schematic of transect for June 2006 field campaigns.

2.3 Field spectra analysis: derivatives and waveband ratios

First derivatives were employed in this study to provide a sensitive analysis of the subtle spectral absorption and reflectance features associated with vegetation stress (Philpot, 1991; Dawson and Curran, 1998). Derivative analysis of the near contiguous bands of field spectra enable the identification of narrow waveband ratios which are tightly coupled to changes in photosynthetic function resulting from vegetation stress (Zarco-Tejada et al., 2003). First derivatives were computed for all spectra, using the finite divided difference approximation method (Chapra and Canale, 1988; Tsai and Philpot, 1998). The derivative peaks were used to select two vegetation band ratios: the vegetation stress ratio of Smith et al. (2004) (exploiting a double peak in the red-edge) and a modified version of this ratio.

The vegetation stress ratio of Smith et al. (2004) exploits the magnitude of the first derivative at 725 and 702 *nm* within the red-edge, which form the mid-point of the red-edge peak maximum and its shoulder. The ratio has enabled identification of stress due to short-term sub-surface gas leaks in grass, and long-term sub-surface gas leaks in winter wheat and bean crops at the canopy scale under controlled field test site conditions. The vegetation stress ratio is obtained by Smith et al. (2004):

$$\frac{725nm}{702nm} \quad (1)$$

Where 725 *nm* is the value of the first derivative of the reflectance spectrum at 725 *nm* and 702 *nm* is the value of the first derivative of the reflectance spectrum at 702 *nm*. The modified vegetation stress ratio takes the form:

$$\frac{723nm}{700nm} \quad (2)$$

Where 723 *nm* is the value of the first derivative of the reflectance spectrum at 723 *nm* and 700 *nm* is the value of the first derivative of the reflectance spectrum at 700 *nm*.

2.4 Soils acquisition and analysis

Soil acquisition was conducted in May 2006 to coincide with field and airborne hyperspectral acquisitions, and to minimise crop disturbance. Sub-soil sampling depth was kept as close as possible to 0.1 – 0.2 m. Soil was extracted at random locations within each of the disturbance zones producing a composite sample for each zone of approximately 500 g (Figure 2). The samples were analysed for organic carbon, Potassium, Phosphorus and pH, to establish if differences in soil fertility were evident between disturbed and undisturbed soil. Indirect measurements of soil strength, structure and compaction were obtained by penetrometer measurements and bulk density core sample extraction in order to validate the penetrometer readings (Bradford, 1986).

3. RESULTS AND DISCUSSION

Field spectroradiometry data were acquired during four field visits in June 2005 and May 2006. A pseudo RGB CASI-2 image overlaid with a red-edge position (REP) blue shift classification (Guyot and Baret, 1988) and pipeline route was used to identify locations where potential vegetation stress coincided with the 508 mm pipeline for the 2005 campaign (Figure 1). Two of the sites of spring barley fields selected as test sites in 2005 are labelled 05B and 05C in Figure 1. Different cropping regimes prevented the use of the same test sites in 2006. New test sites were identified for 2006 based on expert field knowledge from local farmers (Pers. Comm. Donal Cullen, Bruce Mackie and Gerald Banks). One of the sites selected as a test site in 2006, labelled 06A, a winter barley field, (Figure 1) provided the most conclusive results and is the focus of discussion in this paper.

Notable differences in reflectance for crop stress transects are exhibited for winter barley at test site 06A. An increase in reflectance is evident with proximity to the pipeline of up to ~2% at the green peak between 10 and 60 m West (Figure 3). A blue shift in the red-edge of ~5 *nm* is evident with proximity to the pipeline at 25% reflectance. Similar blue shifts in the red-edge for stressed vegetation have also been reported by Jago et al. (1999) and Lelong et al. (1998). Pronounced steps in reflectance occur in the NIR with proximity to the pipeline range between ~19% at 0 m at peak C and ~48% at 70 m West at peak B. The steps in the NIR are most likely to be a direct result of the proportion of soil background to barley leaf coverage, lower NIR reflectance values corresponding with increased soil background proportions, particularly at 0 m and 60 m (Figure 3). The same reflectance responses in the VIS and NIR were also observed by Smith et al. (2004) for soil gassed grass, bean and winter wheat.

Exceptions to this trend occur at 10 m and 20 m West, which display high reflectance throughout the wavelengths sampled, with maximum reflectances of ~54% and ~48% at peak B (Figure 3). The higher reflectance values could be attributed to poor atmospheric conditions during acquisition, when cumulus cloud intermittently obscured the Sun. Another exception is at 60 m West, which has comparatively low reflectance of ~18% at peak C (Figure 3). This is likely due to a combination of increased soil background within the FOV of the ASD spectroradiometer and crop stress (Figure 3).

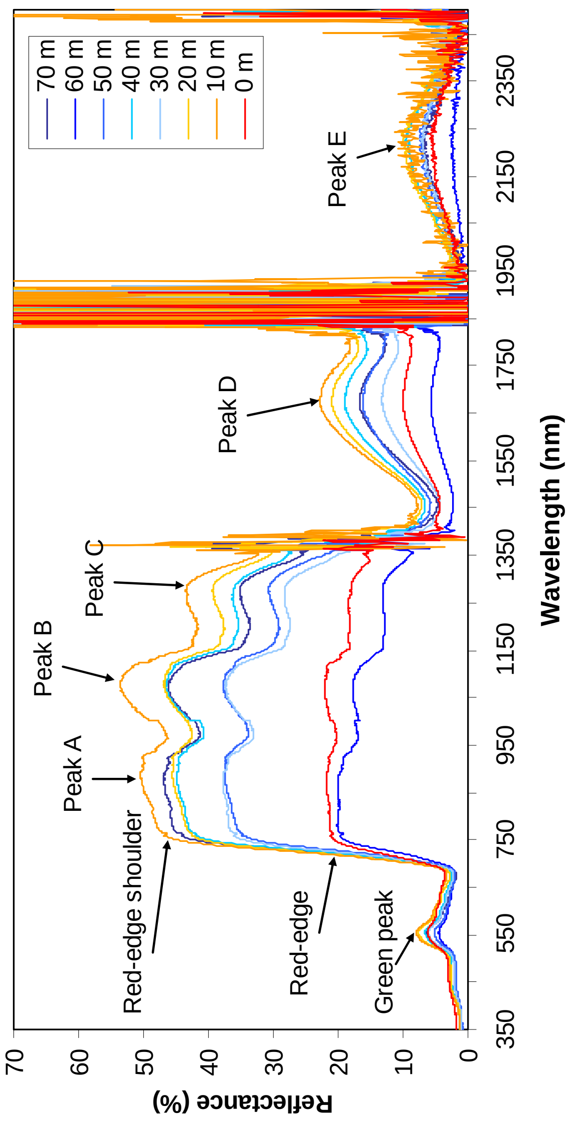


Figure 3. Reflectance of winter barley at site 06A West of pipeline along stress transect on 7th of May 2006. Each line represents reflectance at 10 m intervals along the transect. The noisy regions in the spectra are the result of atmospheric water vapour.

The 2006 first derivative results for winter barley at test site 06A reveal a double peak in the red-edge as reported by Zarco-Tejada et al. (2003) and Smith et al. (2004). First derivatives of the red-edge region change in magnitude, position and shape between the peaks at 700 (A) and 723 *nm* (B). Peak B becomes more pronounced relative to peak A, which maintains the same shape and position with proximity to the pipeline (Figure 4). The West transect limb exhibits notable differences between peaks A and B of up to 0.34 from 0 to 15 m and 0.24 from 20 to 70 m respectively (Figures 4a and b). An exception to this trend is 60 m West, exhibiting a lower red-edge peak, differing by up to 0.34 at peak A and 0.53 at peak B (Figure 5a). The same differences between peaks A and B were also evident along the East transect limb, although less marked. The contrast in the East and West transect limbs could be explained by the location of the vehicle running track to the West of the pipeline (Figure 2). The heavy machinery used to install the pipeline could have led to sub-soil compaction, leading to long-term soil infertility and impeded root penetration which can cause vegetation stress (Rowell and Florence, 1993; Llewellyn and Curran, 2005). These observed differences in first derivatives for winter barley are of the same order of magnitude as those reported by Zarco-Tedjada et al. (2003), Llewellyn and Curran (2005), Smith et al. (2004), and Smith et al. (2005) for a range of vegetation stress inducers (elevated levels of soil gas, herbicide, shade, water, temperature and humidity).

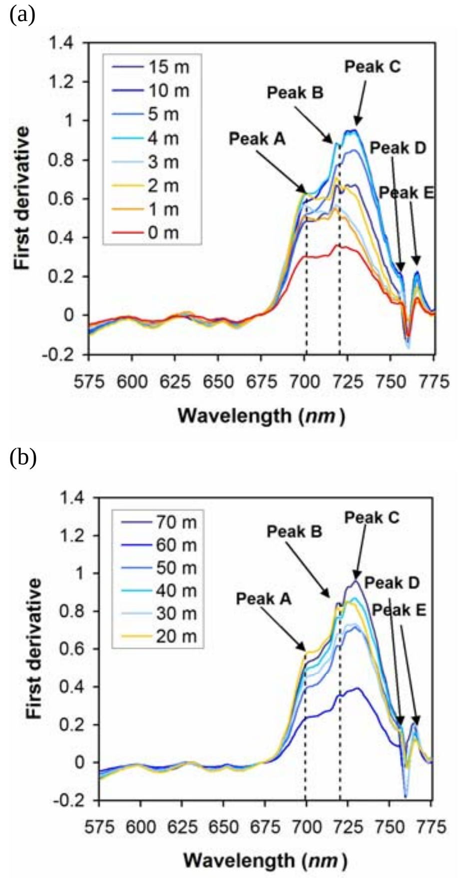
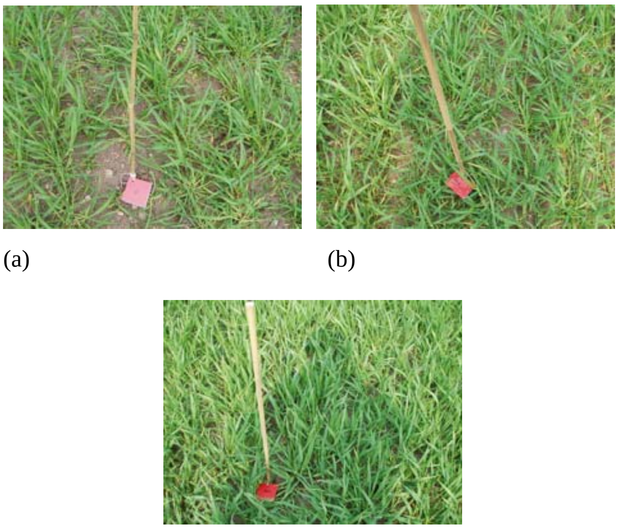


Figure 4. VIS-NIR first derivative of reflectance of winter barley at site 06A along stress transect, on 7th of May 2006: (a) West of pipeline 0-15 m; and (b) West of pipeline 20-70 m. Each line represents reflectance at 1 and 5 m intervals for (a) and 10 m intervals for (b) along the transect.

More marked differences in magnitude between peaks A and B along the stress transect (Figure 4a and b) were observed relative to the control transect. The relative consistency between peaks A and B along the control transect, coupled with their associated proportions of soil background depicted in the nadir photographs at 20 and 40 m West (Figure 5b and c), strongly infer first derivative analysis is detecting vegetation stress and not soil background at test site 06A. An exception to this is at 0 m in close proximity to the pipeline where the proportion of soil background is very marked (Figures 4a and 5a). Moreover, the influence of poor atmospheric conditions at 10 and 20 m West have little influence on differences between first derivative peaks A and B (Figure 4a and b).



(a) (b) (c)

Figure 5. Nadir photographs of sample locations West along stress transect at site 06A on 7th May 2006: (a) 0 m (on pipeline); (b) 20 m from 508 mm pipeline; and (c) 40 m from 508 mm pipeline.

Differences in first derivative ratio values are pronounced for the winter barley stress transect at test site 06A (Figure 6). This corresponds with marked differences between the magnitude in the first derivative peaks at 700 and 723 *nm* (Figure 4a and b). Maximum differences in ratio values on and away from the 508 mm pipeline are 37% for the 723:700 *nm* ratio and 33% for the 725:702 *nm* ratio (Figure 6). The ratios both broadly exhibit the same trend decreasing with proximity to the 508 mm pipeline. To ascertain an estimate for the overall uncertainty in the ratio values obtained for test site 06A the first standard deviation was computed for both ratios. First standard deviations were ±0.24 for the 725:702 *nm* ratio and ±0.23 for the 723:700 *nm* ratio (depicted as error bars in Figure 6), which suggests that the 723:700 *nm* ratio is more robust containing less overall uncertainty (spectroradiometer, weather conditions and the crop). Moreover, maximum differences in the 723:700 and 725:702 *nm* ratios at test site 06A are within the same order of magnitude as those reported by Smith et al. (2004), ranging between 24% and 50% for early gassed grass, bean and wheat.

The soil properties measured associated with sub-surface soil disturbance were able to adequately explain the vegetation stress detected by the first derivative ratios. Student's T-tests revealed that the first derivative 723:700 and 725:702 *nm* ratios were statistically significantly different between stress and no known stress within zones of soil disturbance at the 0.05 confidence level. Regression analysis broadly explained the association between organic carbon and the 723:700 and 725:702 *nm* ratios with differences in variances between predicted and observed values with coefficient of determination values of 0.59 and 0.61. This intimates that the ratios are capable of detecting statistically significant differences in vegetation stress for soil disturbance.

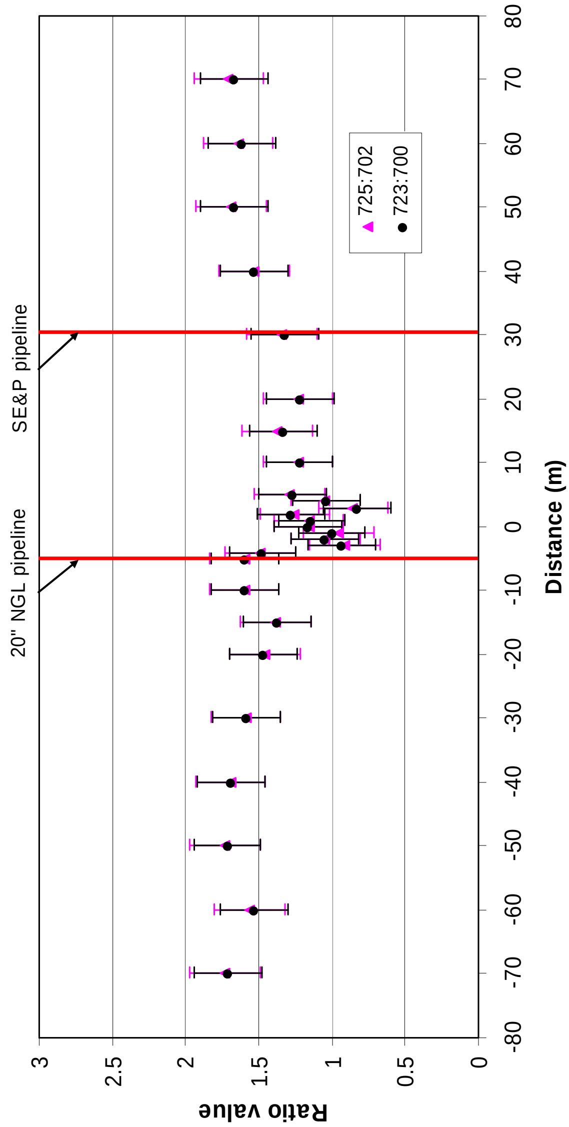


Figure 6. 725:702 and 723:700 ratios of first derivative of reflectance of winter barley at site 06A along stress transect perpendicular to the pipeline, at 1 m (between 0 and 5 m), 5 m (between 5 and 20 m) and 10 m intervals (between 20 and 70 m), on 7th May 2006. Error bars represent estimates of uncertainty computed as ± first standard deviation of the control transect.

4. CONCLUSIONS

This study has demonstrated that the refined experimental design successfully encapsulates the full spatial extent and spectral characteristics of above pipeline vegetation stress. Evidence for this assertion is provided in the ability of the 723:700 and 725:702 *nm* ratios to detect stress above the 508 mm NGL pipeline under a different cropping regimes. Ratio values in 2006 were of the same order of magnitude as the 2005 data and those conducted under controlled conditions by Smith et al. (2004; 2005). The 723:700 and 725:702 *nm* ratios provided consistent results between different test sites and field seasons intimating their transferability to real world operational heterogeneous field conditions at the canopy scale.

This research not only builds directly upon the work conducted by Smith et al. (2004) but also that of Zarco-Tejada et al. (2003) who identified double peak red-edge effects of californium canopies using plant fluorescence detection techniques. Moreover, this paper provides further application of the double peak red-edge feature identified by Smith et al. (2004) and Zarco-Tejada et al. (2003) to infer sub-surface soil disturbance and has wider application areas beyond soil disturbance including archaeology, geophysics and forensic science.

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