APPLYING REMOTE SENSING IN DETECTING PLANTS AFFECTED BY VARIED DOSES OF OIL SPILLS

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Abstract

Spill from oil pipeline is one of the major sources of oil pollution and a threat to man and his environment. To control this menace, frequent, accurate and spatially-comprehensive monitoring and detection of oil spills is required. Remote sensing technologies have this potential by using plant spectral properties. To investigate this, ornamental fountain grass (pennisetum alopecuroides) and deciduous shrub called forsythia (forsythia suspensa) grown in pots were contaminated with refined oil at low, medium, and high levels. Plant heights and spectral measurements were undertaken every week and visual stress symptoms observed. Field portable GER 1500 spectroradiometer was used for all reflectance measurements. Results show a general increase and decrease of the reflectance spectra in the visible and the near infrared regions of the spectrum, respectively. The red region was most sensitive to oil spill at all levels for both plant species. Based on the ratio of change in plant height, both plants were significantly affected by oil spill. Visible stress symptoms observed include: chlorosis, dryness, and growth impairment in all the levels of pollution in both plants. This indicates that by detecting plant stress induced by oil, remote sensing has potential for detecting oil spills. Thus, it suggests further research that may focus in testing the robustness of this approach at larger scale and across species.

Key words: Remote sensing, Spectral reflectance, Plants, Stress, Oil spills.

Introduction

Pipelines are possible source of oil spills as they are susceptible to damage, aging, corrosion, welding and manufacturing anomalies. Spills may also emanate from natural events such as land subsidence and from human activities such as farming, road construction and wilful vandalisation. Contamination of soils with crude oil and refinery products is becoming an ever-increasing problem, especially in the light of several breakdowns of oil pipelines and wells reported recently (Wyszkowski et al., 2004). For safety and security reasons, oil pipelines are kept constantly under surveillance through foot patrol by appointed officials and intermittent aerial surveillance using manual observations from aircraft.

Despite the security and safety measures in place, reports of oil pipeline leaks and spills with disastrous effects continue to rise rapidly (Emengini et al., 2009). The aerial surveillance is costly and has flight risks associated with low level aircraft and rely absolutely on the accuracy of the pilot (Smith et al., 2004). Foot patrol is tedious and time consuming and cannot cover a large area. It is also practically difficult to use in inaccessible areas and hostile environments. If not detected and stopped early, oil leaks can develop into massive spills, leading to fire outbreak which can be very disastrous. This has safety, health, economic and environmental implications including soil contamination, destruction of vegetative ecosystem and arable crops/lands, contamination of surface and underground water, air pollution and extinction of endangered species.

Thus, given the severe limitations and demonstrable ineffectiveness of current surveillance approaches, it is imperative that a technique is developed for frequent, accurate and spatially-comprehensive monitoring and detection of oil pipeline spills. Previous studies found that soil and vegetation are influenced considerably by hydrocarbon pollution. For example, changes have been observed in biochemistry and reflectance in vegetation growing near natural hydrocarbon seeps (Bammel and Birnie 1994, Yang et al., 1999) and leaking gas pipelines (Smith et al., 2000, Smith 2002). Vegetation change around the area of gas leaks has been reported from visual observations by helicopter pilots and pipeline engineers (Smith, 2002). Thus, there is some potential for bio-detection of oil pollution using remote sensing approaches.

Oil is disastrous to plant as it can enter the soil and create unfavourable conditions for plant growth and survival (De Jong, 1980; Günther et al., 1996). It can affect plant through a multitude of different mechanisms, such as soil-oxygen depletion, increased carbon dioxide (CO2), reduced water uptake and toxic effects (Ladjal et al., 2007; Graeff and Claupein, 2007). Toxicity conditions in plant are known to alter leaf pigmentation properties and internal structure which can cause changes in the reflectance spectrum (Rosso et al., 2005). Since the chlorophyll content tends to decrease under stress, the incident solar radiation absorption of the green plant generally results in a decrease in the visible region. Consequently, the spectral reflectance generally is higher in the visible green range depending on the severity of the stress. The strong spectral reflectance of green plants in the near infrared (NIR) range is mainly due to its internal foliar structure. Plants under various stress also show various degrees of internal structural changes, which lead to a decrease of spectral reflectance in the NIR range. These spectral features of plant are the basis of the investigation undertaken in this work. The objective of this study was to explore the potential of remote sensing of plants as a means of detecting oil spills.

Materials and methods

Plant materials and treatments

An ornamental fountain grass (pennisetum alopecuroides) and deciduous shrub called forsythia (forsythia suspensa) plant species were used for the experiment. The plants were grown up to six months in 23cm diameter plastic pots containing a loam-based compost. Four samples, each comprised of ten replicates were established for each of the plant species. These include the control and three dose levels of oil pollution. Diesel was used for treatments and dose levels were low, medium and high levels. The control did not receive oil treatment. The reason for using diesel was for safety reasons as it is relatively less flammable.

The dose levels were estimated based on percentage of soil weight. Systematically, 20%, 40% and 60% of soil weight were chosen to represent low, medium, and high dose levels respectively. Oil was spilled onto the soil surface in order to simulate what generally occurs in the case of oil leakage. During treatments, pots were placed in plastic bowls to collect possible oil that passed through the soil substrate. Oil and water from the pots that settled on the plastic bowl was carefully poured back into the top of the soil once per day during the experiment. Pots were kept outdoors under natural and uniform environmental condition except when plants were taken into a dark room for spectral measurements. The plants were watered on regular basis to avoid onset of water deficit stress.

Spectral measurements

Spectral measurements were undertaken every week. Plants were transferred in their pots from outside to a laboratory for measurements on these occasions. This was to control the influence of other factors on the spectra not related to plant vigour, such as change in illumination angle, atmospheric effects (Mutanga et al., 2003, Vaiphasa, et al., 2005) and areas of shadow (Blackburn, 2007).

Field portable GER 1500 spectroradiometer was used for all reflectance measurements. The GER 1500 uses a diffraction grating with a silicon diode array that has 512 discrete detectors that provides the capability to read 512 spectral bands. Thus, it scans the spectrum at approximately 1.5 nm intervals and covers a portion of the Ultraviolet (UV), the Visible, and the Near-infrared (NIR) wavelengths from 350 nm to 1050 nm. With a standard 4o field of view fore-optic, the sensor was mounted in a fix position at about 1.5 m above the canopy at the nadir position. To fully illuminate the target, a 500W halogen lamp was mounted at a fixed position next to the sensor, at a zenith angle of 45o. Prior to scanning, the lamp was switched on for about 20 minutes to eliminate spectra changes in the lamp as it warmed up (Smith et al., 2004). 10 spectral measurements per canopy were taken for all samples.

Scans of the spectralon reference panel and canopy were taken in succession in order to minimise changes in irradiance between the two measurements. Percentage spectral reflectance (R) was computed by dividing the radiation reflected from the canopy (It) by that reflected from the white spectralon reference panel (Ir) and applying a correction (k) for the spectral reflectance properties of the panel, as no perfectly reflecting panel exist in practice (Milton, 1987).

Plant height measurements and physical observations

Plant height was measured on all the samples for each of the plant species. The height was measured from the level of the soil surface to the apex of the largest shoot in the individual plants using a 3m measuring tape. Height measurements were undertaken on a weekly basis to monitor how oil was affecting plant growth. Development of stress symptoms was visually observed every week.

Data analysis

Spectral data analysis

The spectral data were processed after importing the GER1500 .sig files into Microsoft Excel using a Visual Basic macro. Individual reflectance spectra were displayed and visually assessed to eliminate erroneous data. Differences between the initial spectral reflectance of control and treatments were computed. These were used to normalise subsequent spectral reflectance of treatments. This was to ensure a meaningful comparison between changes in spectral reflectance of control and treated plants. In order to examine the effect of treatments on plant spectral properties, the mean reflectance spectra of control and treatments were plotted against wavelength. However, wavelengths shorter than 400 nm were not analysed due to excessive noise. Differences between the mean reflectance spectra of treatments and control were computed and plotted in order to ascertain how oil impact the spectral properties plants.

Statistical analysis

Wavelengths considered for analysis were based on systematic selection of different spectral regions that is, the blue (400-500nm), green (500-600nm), red (600-700nm), near infrared (700-800nm) and far infrared (800-900nm). With respect to these spectral regions, wavebands at which the reflectance difference between the treated plants and controls were high were selected for statistical analysis. This was to ascertain whether change in their spectral reflectance were statistically different. The hypothesis tested was that there is no significant difference between changes in spectral reflectance of control plants and those treated with oil at different levels. Analysis of Variance (ANOVA) comparisons were used to test the hypothesis. Where the spectral reflectance of control and treated plants was statistically different, further analysis was carried out using Post hoc multiple comparisons to ascertain which samples were different. Average plant height for each sample of the two plant species was calculated and total difference in plant height computed at the end of the experiment. Differences in plant height were examined for significant difference using Wilcoxon signed-rank test.

Results and discussion

Visual stress symptoms

Treated plants of both grass and forsythia were visually affected by oil pollution as shown in figures 1 and 2 respectively. A variety of visible stress symptoms ranging from stunting, leaf chlorosis and shoot mortality were generally observed in all treated plants as summarised in table 1. Stress symptoms appeared earlier in grass than forsythia. The first visible symptoms were observed in grass five days after oil treatment. In forsythia, visible stress symptoms appeared at about two weeks after treatments commenced. The control plants of both species never showed any sign of stress but flourished throughout the experimental period.

Figure 1. Visual stress symptoms developed by grass 28 days after treatments at varied levels commenced. C = control, L = low, M = medium, H = high

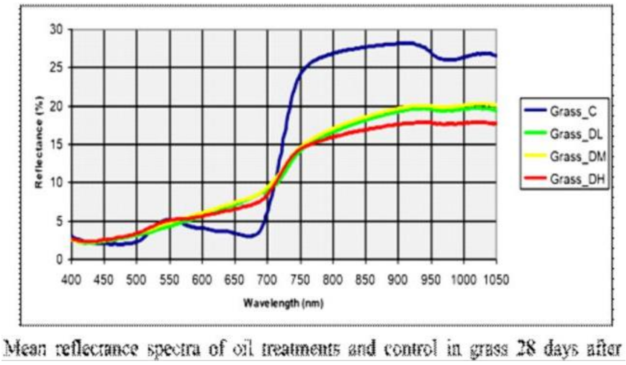
Figure 2. Visual stress symptoms developed by forsythia 28 days after treatments at varied levels commenced. C = control, L = low, M = medium, H = high.

Table 1: Visual stress symptoms of grass and forsythia treated with oil pollution at varied levels. C = Control, L = Low, M = Medium, 11 = High

Plant specie	Treatments	Visual stress symptoms				
		Day 0	**Day 7**	**Day 14**	**Day 21**	**Day 28**
Grass	L	Booming with green healthy leaves	Leaves dehydrated and changed to reddish brown	Same symptoms but with an increased rate	Symptoms affecting the entire plant	Plant completely dehydrated
	M	Same as low	Same as low	same as low but more severe	The whole plant were affected	Dehydrated plant
	H	Same as low	Same as low but involving more leaves	Virtually all leaves were affected	Completely dehydrated	Completely dehydrated
Forsythia	L	Same as above	Leaves still look healthy and green	Still green	Few leaves changed to reddish-brown	Few leaves changed to reddish-brown
	M	Same as above	Same as above	Chlorosis in fewer leaves	Same as low	More severe
	H	Same as above	Same as above	Leaf chlorosis affecting more leaves	Same as medium but severe	Same as medium but more severe

Plant spectral response

The spectral reflectance of treated plants generally increased in the visible and decreased in the NIR region of the spectrum relative to control. Figures 3 and 4 show the mean reflectance of the treated plants and controls on the final day of the experiment. The pattern of reflectance changes generally follows the dose level. The only exception is where grass treated with low dose had a slightly lower reflectance than medium treatment throughout the spectrum (figure 3).



Mean reflectance spectra of oil treatments and control in grass 28 days after

Figure 3: Mean reflectance spectra of oil treatments and control in grass 28 days after treatments commenced. Grass--_C = Control, Grass_DL = Low Dose, Grass_DM = Medium Dose, Grass_ DH = High Dose

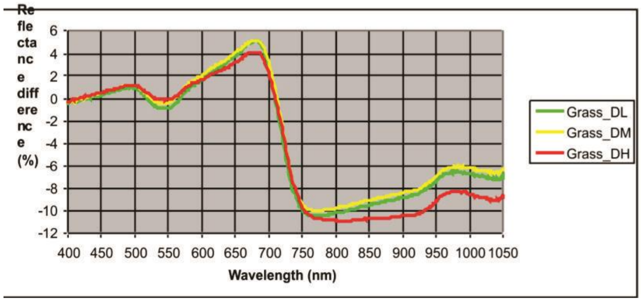


Figure 4: Difference between mean spectra of oil treatments and control in grass 28 days after treatments commenced. Grass_DL = Low Dose, Grass_DM = Medium Dose, Grass_DH = High Dose

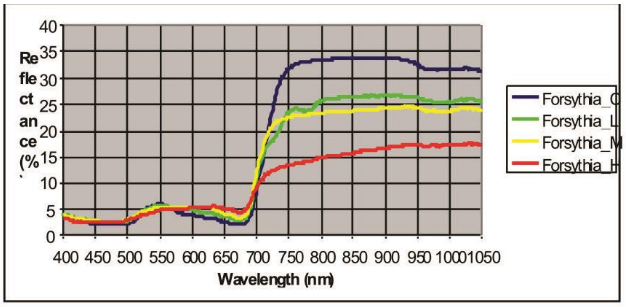


Figure 5: Mean reflectance spectra of oil treatments and control in forsythia 28 days after treatments commenced. Forsythia_C = Control, Forsythia_DL = Low Dose, Forsythia_DM = Medium Dose, Forsythia_ DH = High Dose

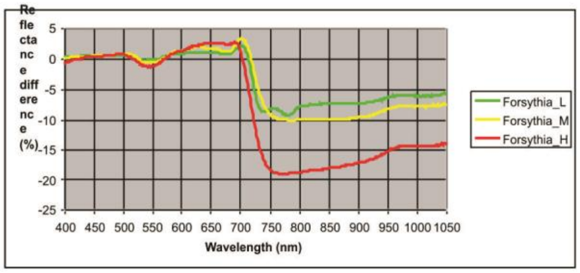


Figure 6: Difference between mean spectra of oil treatments and control in Forsythia 28 days after treatments commenced. Forsythia_DL = Low Dose, Forsythia_DM = Medium Dose, Forsythia_DH = High Dose.

Table 2 shows a summary of ANOVA testing for significant differences between the spectral reflectance of control and treated plants. Oil treatment at no level had significant effect on the spectral reflectance of both plant species in the blue and green regions. Oil at all levels of treatment had significant affect on the spectral reflectance of grass and forsythia in the red region. In the NIR, treatments at all levels had significant effect on grass spectral reflectance. Medium and high levels of treatment significantly affect forsythia in the same region. At longer wavelength in the NIR, treatments at all levels of treatment also had significant effect on grass spectral reflectance. For forsythia, significant difference was found only at medium and high levels of treatment at longer wavelength in the NIR.

Table 2: ANOVA showing significant difference in spectral reflectance changes of grass and forsythia treated with oil at different levels. In the wavelength column, subscripts G and F refer to grass and forsythia respectively. C = Control, L = Low, M = Medium, H = High.

Wavelength (nm)	**Treatments**	**Plant species**	
		Grass	**Forsythia**
494.7_G, 401.2_F	**L**	0.071	0.708
	M	0.405	0.954
	H	0.617	0.089
598.6_G, 550.8_F	**L**	0.082	0.080
	M	0.509	0.084
	H	0.881	0.493
681.1_G, 698.6_F	**L**	0.000*	0.020*
	M	0.000*	0.002*
	H	0.000*	0.000*
700.2_G, 798.5_F	**L**	0.000*	0.085
	M	0.002*	0.003*
	H	0.007*	0.000*
800.1_G, 877.7_F	**L**	0.000*	0.115
	M	0.000*	0.003*
	H	0.000*	0.000*

Plant Height

Both grass and forsythia heights generally decreased with stress irrespective of level of oil pollution (table 3). The grass height generally decreased with increased dose level. Forsythia had similar response, although it did not follow dose level. There was significant difference ($p = 0.026 < 0.05$) between the effects of oil pollution on the heights of the treated plants and control.

Table 3: Effects of Oil Pollution on Plant Height. C = Control, L = Low, M = Medium, H = High

Plant Specie	**Treatments**	**Mean height (cm)**			**Mean height gain/loss (cm)**		
		Day 0	**Day 7**	**Day 14**	**Day 21**	**Day 28**	
Grass	**C**	83	85	90	91	92	9
	L	84	83	83	83	64	-20
	M	83	82	80	66	35	-48
	H	90	85	74	40	25	-65
Forsythia	**C**	48	48	49	50	52	4
	L	52	53	51	49	46	-6
	M	60	60	60	59	46	-14
	H	37	38	37	34	30	-7

Discussion

Visible stress symptoms such as leaf and stem chlorosis, dryness, and growth impairment were observed in all the dose levels of pollution in both plants. However, stress symptoms first developed in grass than forsythia. Similarly, earlier studies using a wide range of plant species and stresses also discovered the first visual signs of stress at different times after inducement (Ketel, 1996; Smith et al., 2004; Smith et al., 2005). These variations suggest that the time of first visible stress symptom is a function of plant species, type and degree of stress. In this study, forsythia appears to be more resistant to oil pollution than grass (as grass reached mortality level while forsythia did not). This could possibly be attributed to its strong root system that may have stored sufficient resources needed to sustain plant growth. Symptoms at all dose levels started mildly by affecting only a few leaves and gradually becoming severe by spreading over all the leaves. The visible stress symptoms progressed in a way similar to that observed in oilseed rape leaves affected by natural gas elevation in the soil and other stresses (Smith et al., 2005).

There was a general change in the spectral reflectance of treated plants. Generally, the reflectance spectra increased in the visible and decreased in the NIR regions of the spectrum. It was found that the blue and green regions were generally not sensitive to oil pollution at all levels. This result concurs with the findings of Emengini (2010), where the blue (R450) and green (R550) regions were unresponsive to oil-induced stress in maize. Most pigments such as α-carotenoid, ß-carotenoid, and anthocyanins absorb either in the blue or green region but only chlorophyll absorbs in the red region (Gates et al., 1965). These pigments and weak absorption of chlorophyll in the green region (Smith (2002), Blackburn (2007) may be responsible for the poor reflectance change as oil pollution may not have affected them.

The red region appears to be most sensitive to oil pollution at all levels for both plant species. This observation was similar to findings of Smith et al., (2005) where the waveband in the red region increased rapidly in the gas and herbicide-stressed plants. Furthermore, previous study found significant change in spectral reflectance mainly in the red-edge region of the spectrum particularly across 650nm to 720nm. A study by Carter (1993) found that increased reflectance in the 685 to 700nm wavelengths range was constantly sensitive to different stresses across species. This finding is expected as it is the region of strong chlorophyll absorption. Since chlorophyll is responsible for light absorption particularly in the red, a higher reflectance exhibited by the polluted plants in this region implies a decrease in chlorophyll content.

A decrease in the NIR reflectance found in this study is similar to the results of Pickerill and Malthus (1998) and Smith et al., (2005). Pickerill and Malthus (1998) found that the NIR reflectance was lower for wheat crops growing over the leaks from rural aqueducts than the surrounding canopy due to the reduced plant biomass and the presence of standing water and wetter soil. It is known that a number of factors such as the size of the cells, the number of cell layers and the thickness of the leaf mesophyll influence NIR reflectance. The results suggest that oil pollution may have damaged the leaf internal structures causing significant decrease in reflectance observed in this region.

Based on the ratio of change in plant height, both plants were significantly affected by oil pollution. The adverse effects of oil pollution on economic plants have been reported (Amadi et al., 1993; Anoliefo and Okoloko, 2000). At high concentrations of oil in soil, most plants species suffered serious depression in growth (Amakiri and Onoteghara, 1984). This condition has been attributed to poor soil conditions, dehydration and impaired nutrient uptake by the roots, created by the presence of crude oil (Anoliefo et al., 2003). However, from the progression of stress observed in forsythia, one can predict that mortality will occur if the experiment is continued for a longer period than that used in the present experiment. This suggests that irrespective of level of oil pollution, duration of exposure could also count as an important factor for assessing plant damage by oil pollution.

Conclusion

Plants have different levels of sensitivity to stress, but can generally respond quickly to high level of pollution and slowly if contaminated at a sub lethal level. Plant height, visual observation and spectral reflectance features have potential for monitoring oil pollution. Overall, spectral reflectance, particularly in the red region, is a potential indicator of leaks from oil pipelines (at lethal and sub-lethal levels) that could be applicable across different plant species. Finally, this study indicates that the use of spectral properties of plants as an indicator of oil-induced stress is worthy of further investigation, that may focus on testing the robustness of this approach across species and scales. Consequently, this shall be explored further in subsequent experiments.

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References

Amadi, A., Dickson, A. A., and Maate, G. O., 1993. Remediation of polluted soil I. Effect of organic and inorganic nutrient supplements on the performance of maize (zea mays). Water, Air and Soil Pollution, 66, pp. 59-76.

Amakiri, J. O., Onoteghara, F. A., 1984. Effects of crude oil pollution on the growth of Zea Mays, Abelmosvhus esculentus and Capsicum frutescans. Oil and Petroleum Pollution, 1(3), pp. 199-206.

Anoliefo, G. O., and Okoloko, G. E., 2000. Comparative toxicity of forcados blend crude oil and its water soluble fraction on seedlings of Cucumeropsis Manni Naudin. Nigeria Journal of Applied Science, 18, pp. 39-49.

Anoliefo, G. O., Vwioko, D. E., and Mpamah, P., 2003. Regeneration of Chromolaena Odorata (1) K. and R. incrude oil polluted soil: a possible phytoremediating agent. Benin Science Digest, 1, pp. 78-82.

Bammel, B. H., and Birnie R. W., 1994. Spectral response of big sagebrush to hydrocarbon-induced stress in the Bighorn Basin, Wyoming. Photogrammetric Engineering and Remote Sensing, 60, pp. 87-96.

Blackburn, G. A., 2007. Hyperspectral remote sensing of plant pigments. Journal of Experimental Botany, 58 (4), pp. 855-867.

Carter, G. A., 1993. Responses of leaf spectral reflectance to plant stress. American Journal of Botany 80, pp. 239-243.

De Jong, E., 1980. The effect of a crude oil spill on cereals. Environmental Pollution, 22, pp. 187-196.

Emengini, E. J., 2010. Hyperspectral and thermal remote sensing of plant stress response to oil pollution. Ph.D thesis, University of Lancaster, UK, pp. 103.

Emengini, E. J., Blackburn, A. G., and Theobald, J. C., 2009. Spectral indices out-perform thermal signals for early detection of oil pollution in maize (Zea mays, L.). Proceedings of the 33rd International Symposium on Remote Sensing of Environment (ISRSE), Stressa, Italy. 8-11th May, 2009.

Gates, D. M., Keegan, H. J., Schelter, J. C., and Weidner, V. R., 1965. Spectral properties of plants. Applied Optics, 4 (1), pp. 11-20.

Gong, P., Pu, R., and Heald, R.C., 2002. Analysis of in situ hyperspectral data for nutrient estimation of giant sequoia. International Journal of Remote Sensing, 23, (9,) pp. 1827-1850.

Graeff, S., and Claupein, W., 2007. Identification and discrimination of water stress in wheat leaves (Triticum aestvum L.) by means of reflectance measurements. Irrigation Science, 26, pp. 61-70.

Günther, T., Dornberger, Utz., Fritsche, W., 1996. Effects of ryegrass on biodegradation of hydrocarbons in soil. Chemosphere, 33, (2), pp. 203-215.

Isirimah, N. O., Zoufa, K., and Loganathan, P., 1989. Effect of crude oil on maize performance and soil chemical properties in the humid forest zone of Nigeria. Discovery and Innovation, 1(3), 95-98.

Ketel, D. H., 1996. Effect of low doses of metamitron and glyphosphate on growth and chlorophyll content of common lambsquarters (Chenopodium album). Weed Science, 44, pp. 1-6.

Ladjal, M., Deloche, N., Huc, R., and Ducrey, M., 2007. Effects of soil and air drought on growth, plant water status and leaf gas exchange in three Mediterranean cedar species: Cedrus atlantica, C. Brevifolia and C. Libani. Trees, 21, pp. 201-213.

Milton, E. J., 1987. Principles of field spectroscopy. International Journal of Remote Sensing, 8 (12), pp. 1807-1827.

Mutanga, O., Skidmore, A., and Van Wieren, S., 2003. Discriminating tropical grass (Cenchrus ciliaris) canopies grown under different nitrogen treatments using spectroradiometry. ISPRS Journal of Photogrammetry & Remote Sensing, 57, pp. 263-272.

Odu, C. T., 1981. Degradation and weathering of crude oil under tropical condition. The petroleum industry and the Nigerian environment. In: Proceedings of the International Seminar by the NNPC, PTI, Warri, pp. 164-170.

Pickerill, J. M., and Malthus, T. J., 1998. Leak detection from rural aqueducts using airborne remote sensing techniques. International Journal of Remote Sensing, 19, pp. 2427-2433.

Rosso, P. H., Pushnik, J. C., Lay, M., and Ustin S. L., 2005. Reflectance properties and physiological responses of Salicornia virginica to heavy metal and petroleum contamination. Environmental Pollution, 137, pp. 241-252.

Smith, K. L., 2002. Remote sensing of leaf responses to leaking underground natural gas, Ph.D thesis, University of Nottingham, UK, pp. 4.

Smith, K. L., Steven, M. D. and Colls, J. J., 2004. Spectral responses of pot-grown plants to displacement of soil oxygen. International Journal of Remote Sensing, 25 (20), pp. 4395-4410.

Smith, K. L., Steven, M. D., and Colls, J. J., 2000. Remote sensing of vegetation stress due to leaking underground pipelines. Aspects of Applied Biology, 60, pp. 209-212.

Smith, K. L., Steven, M. D., and Colls, J. J., 2005. Plant spectral responses to gas leaks and other stresses. International Journal of Remote Sensing, 26 (18), pp. 4067-4081.

Udo, E. J., and Fayemi, A. A., 1975. The effect of oil pollution of soil on germination, growth and nutrient uptake of corn. Journal of Environmental Quality, 4, pp. 537-540.

Vaiphasa, C., Ongsomwang, S., Vaiphasa, T. and Skidmore, A. K., 2005. Tropical mangrove species discrimination using hyperspectral data: A laboratory study. Estuarine, Coastal and Shelf Science, 65, pp. 371-379.

Wyszkowski, M. J., Wyszkowska J., and Ziółkowska A., 2004. Effect of soil contamination with diesel oil on yellow lupine yield and macroelements content. Plant, Soil and Environment, vol. 50, pp. 218-226.

Yang H., Zhang J., Van der Meer, F., and Kroonenberg§ S. B., 1999. Spectral characteristics of wheat associated with hydrocarbon microseepages. International Journal of Remote Sensing, 20 (4), pp. 807-813.