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Remote Sensing Technology: An Indispensable Tool For Combating Oil Pollution Via Plant Stress Response

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Abstract

Problems of oil pollution and ways of abating them remain a subject of growing concern. Remote sensing technology has been identified as a practical tool for monitoring vast areas of land surface including ecological studies that relates to monitoring plant health status. The approach is based on the understanding that unfavourable growing conditions result in morphological, physiological and/or biochemical changes that impact on the manner with which plants interact with light. The critical issue is the choice of appropriate remote sensing system for plant stress monitoring as the information about the general health status of vegetation is often embedded in narrow spectral features. Several indicators have been used successfully to diagnose plant stress but a definite way of discriminating between the stresses remains a challenge. Also, among these plethoras of successful diagnostic stress indicators, the optimal indicator for monitoring plant stress induced by oil pollution has not well been established. The majority of the tested indicators were based primarily on laboratory or greenhouse scale study and therefore, there is a need to test this approach under field conditions and at a larger scale. Unfortunately, the available satellite remote sensing systems are unable to offer both high spatial and high spectral resolution required for capturing the health status of plant but airborne systems do have this capacity.

Keywords: *Oil pollution, Plant stress, Remote sensing, Spectral reflectance.*

1. Introduction

Alongside the huge benefits derived from the oil and gas exploration and exploitation industries, is ever increasing environmental degradation. Oil pollution can arise from accidental oil well blow out, loading activities of oil tanks, tank washing activities of ocean going vessels, port and harbor run off from pipeline leaks and road tanker accidents. Equipment failure such as malfunctioning, overloading, corrosion or abrasion of parts has also increased the incidence of oil pollution (Nwankwo and Ifeadi, 1986). In recent years, wilful vandalisation of oil pipelines, particularly in some locales, has also contributed to the menace.

If not detected and stopped early, oil pollution especially those from pipeline leaks and storage facilities 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, identification of the best approaches for monitoring and detecting oil spills in the environment remain a subject of growing concern.

The current method of monitoring oil facilities for possible leaks using 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.*, 2004a). Manual observation using 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. 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 pollution.

Stress condition in plants is visible in the spectra (Knipling, 1970; Noomen *et al.*, 2003; Kempeneers *et al.*, 2005) thus, making remote sensing a valuable tool for early detection of plant stress (Rosso *et al.*, 2005). Previous investigations have 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 (Lang *et al.*, 1985 and Bammel and Birnie 1994, Yang *et al.*, 1999) and leaking gas pipelines (Pysek and Pysek, 1989, Smith *et al.*, 2000, Smith 2002b). Furthermore, vegetation change around the area of gas leaks has been reported by Smith (2002a). Thus, there is some potential for bio-detection of oil pollution using remote sensing approaches. The primary aim of this study was to explore the physiological basis for using remote sensing techniques for monitoring the vegetation as a means of detecting oil pollution. The specific objective was to determine the efficacy of spectral properties of plants as indicators for oil pollution.

2. Effects of oil on soil

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). Oil can change the mineralogy of the soil and can displace soil air, including the oxygen. Indeed, previous studies noted that oil leads to depletion of oxygen or insufficient aeration in the soil (Rowell, 1977; De Jong, 1980; Schumacher, 1996; Noomen *et al.*, 2003) and prevents water from entering the soil layers (Wyszkowski *et al.*, 2004). Soil fertility is influenced by the activity of bacteria and fungi, thus, oxygen deficit in the soil gives rise to changes in the reduction-oxidation potential and soil pH. The pH of the oil-impacted soils was found to be significantly lower than the uncontaminated soils (Osuji and Nwoye, 2007). This was attributed to possible disruption of leaching of basic salts which are responsible for raising pH in non-contaminated soils. In general, these activities create imbalances in the metabolic functions of plant organisms, thereby introducing stress, as their normal growth and general health condition are disrupted. Soil - oxygen is further reduced by an increase in demand for oxygen brought about by the activities of oil-decomposing micro-organisms (Gudin and Syratt, 1975). Lee and Banks (1993) found that the microbial plate counts in petroleum contaminated vegetated soil were significantly higher than those of un-vegetated contaminated soil. This indicates that plant roots stimulate microbial populations in polluted soils which promote degradation of contaminants. On the other hand, as the microbial population in the soil increases demand for oxygen also increases. Overall, soil aeration can be depleted if the rate at which oil gets into the soil is faster than the rate the oil is degraded by microbes.

Furthermore, when oil covers the soil surface, oxygen movement into the soil is restricted which can lead to more anaerobic soil conditions (Ranwell, 1968). Apparently, CO_2 increases with decrease in O_2 thus, depletion of O_2 in the soil as a result of effects of hydrocarbon and activities of microbial will invariably lead to increased concentration of CO_2 in the soil (Hillel, 1998). Accumulation of CO_2 in the soil may affect the water permeability of roots more directly than O_2 deficiency and a buildup of inhibitory concentrations of ethylene in anaerobic soils may affect plant growth (Trought and Drew, 1980a). Soil O_2 depletion can disrupt root metabolism which, in turn, can affect the hormone balance of the shoot (Trought and Drew, 1980b). Generally, oil has adversely affected soil drainage. Earlier studies found that oil reduced water infiltration (Toogood, 1977; Everett, 1978) in mineral soils and this was attributed to a decrease in soil permeability resulting from the formation of hydrophobic films on soil particles. Similarly, Gill *et al*. (1992) reported that fresh crude oil showed a coagulatory effect on the soil, binding the soil particles into a water impregnable soil block which seriously impair water drainage and oxygen diffusion. Gassed soil deteriorates soil drainage so that the soil constantly puddled (Schollenberger, 1930; Hoeks, 1972). Godwin *et al*. (1990) also found that the soil drainage was decreased in the vicinity of gas wells and that puddles formed at the surface.

Oil reduces the available nitrogen content of the soil (Sojka *et al.*, 1975; Jong, 1980) which results from consumption of all available nitrogen by bacteria and fungi growing on a hydrocarbon medium in soil thus, restricting the uptake of these elements by plants (Małachowska-Jutsz *et al.*, 1997; Xu and Johnson, 1997). These activities are caused by a depression in ammonification and nitrification processes triggered by inhibition in conversion of mineral and organic nitrogen compounds in soil by petroleum derived compounds (Iwanow *et al.*, 1994; Amadi *et al.*, 1996). Oil degrading or hydrocarbon-utilizing microbes such as *Azobacter* spp. have been reported to become more abundant while nitrifying bacteria such as *Nitrosomonas* spp. become reduced in number (Odu *et al*., 1985) in oil contaminated soil. Osuji and Nwoye (2007) suggest that the process of nitrification might have reduced following the incidence of oil spillage which has led to reduction in the concentration of nitrate-nitrogen (NO_3-N) in oil contaminated sites.

Furthermore, contamination of soil with refinery products modifies the structure and appearance of the soil and deteriorates its biochemical and physicochemical properties (Tyczkowski, 1993; Kucharski and Wyszkowska, 2001; Wyszkowska *et al.*, 2002; Wyszkowski *et al.*, 2004). Schollenberger (1930) and Hoeks (1972) found that the gassed soil was darker than the ungassed soil, and the normal structure of the soil was lost. Several studies have indicated that soil polluted by petroleum-based products loses its biological activity and may not recover it over ten years (Sparrow and Sparrow, 1988; Racine, 1993). A recent study noted that the greasy texture of hydrocarbons, in excessive amount in the soil, is responsible for the prevailing amounts of organic carbon over those of nitrogen in soil (Wyszkowski *et al.*, 2004). Partial coating of soil surfaces by the hydrophobic hydrocarbons might reduce the water holding capacity of the soil due to some significant reduction in the binding property of clay (Osuji and Nwoye, 2007). Usually, such partial coats lead to a breakdown of soil structure and the dispersion of soil particles, which reduce percolation and retention of water. Osuji *et al*. (2006b) found that soils develop severe and persistent water repellency following contamination with crude oil. The coupling effects of this and exhaustion of oxygen in the soil can increase the microbial activity and thus interfere with the plant-soil-water relationship. This can affect plants general growth and productivity.

3. Effects of oil on plants

Studies show that plants are important productive resources but very vulnerable in the event of an oil spill (West *et al.,* 2005). They are highly susceptible to oil exposure and this may kill them within a few weeks to several months (Omosun *et al*., 2008). Thus, they are considered number one priority in oil spill response assignments. It has been discovered that very often, it is difficult to get rid of the oil from the environment once contaminated; hence lots of damage is done as oil persist therein for many years (Gundlach & Hayes, 1978). Both heavy metals and petroleum oils are known to cause stress in plants (Mendelssohn *et al.*, 2001). The adverse effects of oil pollution on economic plants have been reported (Odu, 1981; Isirimah *et al*., 1989; Amadi *et al*., 1993; Anoliefo and Okoloko, 2000). At high concentrations of oil in soil, most plants species suffered serious depression in growth (Udo and Fayami, 1975; 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).

Oil spills directly or indirectly contaminate plants in several ways. Oil can enter the soil and create unfavourable conditions for plant growth and survival (De Jong, 1980; Günther *et al.*, 1996). For example, Edema *et al*. (2009) noted that crude oil reduced phosphate, sulphate and nitrate ionic concentrations in soils and thus, oil spillage could make vital plant nutrients unavailable to plants (Odu, 1981). Also, it was found that oil markedly reduced water uptake by wheat from contaminated layers or below such layers (Jong, 1980) and that water absorption may be inhibited after long periods of anaerobis (Smith, 2002b). On the other hand, plants can be directly affected through physical contact with oil, for example, through coating of plant foliage (Pezeshki *et al.*, 2000), especially when plant canopies grow over the land surface. Coating of plant leaves by oil causes stomatal closure and consequently, an increase in leaf temperature because of blocked transpiration pathways (Pezeshki and DeLaune, 1993). However, it is not clear whether similar thermal effects occur in plants that are indirectly exposed through oil contamination of soil.

Stomatal closure also reduces leaf photosynthesis because of restricted entry of CO_2 through stomatal pores (Pezeshki and DeLaune, 1993; Pezeshki *et al.*, 1995). Other workers have mentioned the effects of crude oil on the growth and physiology of different plants (Cook and Westlake, 1974; Terge, 1984; Gill *et al*., 1992; Pezeshki and DeLaune, 1993;. Previous studies have mentioned that the crude oil penetrates the pore spaces of terrestrial vegetation (Bossert and Bartha, 1984) and subsequently impedes photosynthesis and other physiological processes of the plant (Odu, 1977, 1981). Through physical contact, refined and light oil in particular, can penetrate into plants/leaf tissue and consequently, destroy cellular integrity, and prevent leaf and shoot regeneration (Webb, 1994; Pezeshki *et al.*, 1995; Pezeshki *et al.*, 2000). The adverse effects of petroleum and its compounds on plant growth have earlier been reported by Gill *et al*. (1992). Also, the inhibition of plant growth by harmful metallic ions present in petroleum was reported by Winter *et al*. (1976).

It has been found that oil penetrating and accumulating in plants can cause damage to cell membranes and leakage of cell content (Baker, 1970). Consequently, it has been observed that oil affects germination, plant height, grain yield, and dry matter content of crops especially when pollution is heavy (Ogboghodo *et al*., 2004). A recent study noted that soils contaminated with crude oil contain polycyclic aromatic hydrocarbons (PAH) and heavy metals that are toxic to plants (Edema *et al*., 2009). Crude oil is phytotoxic because it creates unsatisfactory conditions for plant growth ranging from heavy metal toxicity to inhibited aeration of the soil. Edema *et al*. (2009) also found that the nature of crude oil and its components was responsible for the low number of plant families encountered in the field. Toxicity symptoms observed in plants exposed to oil pollution include chlorosis, necrosis, stunted growth, suppression of leaves, enormous reduction in biomass to stomatal abnormalities (Baker, 1970).

In some salt-tolerant plants, petroleum hydrocarbons may damage root membranes, thereby adversely affecting the ionic balance of the plants and their ability to tolerate salinity (Gilfillan *et al.*, 1989). Further investigations have found that the growth of cereal in oil polluted soil was inhibited, with leaves undergoing chlorosis and general plant dehydration (Udo and Fayemi, 1975). Oxygen is generally obtained from the soil and is required for correct functioning of plant roots (Smith, 2002a). It is necessary for aerobic respiration and the supply of metabolic energy, which is used for the production of new root cells for growth and for the uptake of nutrients from the soil (De Wit, 1978). Therefore absence or insufficient oxygen in soil caused by oil pollution can lead to plant death.

Spartina alterniflora is an important coastal salt-marsh species and is particularly susceptible to coastal oil slicks thus; considerable attention has been drawn towards investigating their response to oil pollution as illustrated in Pezeshki *et al.* (2000). Several studies found that accumulation of high levels of crude oils in the soil resulted in the death of *Spartina alterniflora* (Krebs and Tanner, 1981; Alexander and Webb, 1987). A similar study using the same species found that leaves died after about 40 days of contamination (Pezeshki *et al.*, 1995). Overall, oil pollution reduces plant transpiration and carbon fixation and increases plant mortality (Baker, 1970; Pezeshki and Delaune, 1993). However, the extent of damage highly depends on a number of factors for example; season of spill, soil type, oil type and these were extensively discussed in Pezeshki *et al.* (2000). Overall, plant stress whether directly or indirectly induced by oil pollution can cause harmful effects on vegetation leading to growth inhibition, early senescence, chlorosis, dehydration, and death.

4. Remote Sensing of plant stress

Today, there is a growing and considerable interest in the study of plant stress caused by biotic and abiotic stress factors using remote sensing techniques. These techniques make use of variety of sensors that span the optical to microwave regions of the electromagnetic spectrum. Remote sensing is broadly defined as the science of acquiring information about an object with a device without being in physical contact with it. In general, the process requires measuring the interactions between matter and electromagnetic radiation to identify properties and processes of the object of interest. These interactions are controlled by the physical, chemical and biological characteristics of the object (Liew *et al.*, 2008) which, in turn, control its remotely-sensed response. Incident radiation (I) on a plant leaf is either reflected (R), absorbed (A), or transmitted (T), as illustrated in Figure 1, and their relative proportions vary with the wavelength of radiation. The absorbed energy may be subsequently emitted by the object. Remote sensing systems record the reflected and emitted energy which, when processed appropriately, can reveal information about the object measured.

Fig. 1 Interaction of incident electromagnetic radiation with plant leaf.

4.1. The spectral reflectance of plants

The spectral 'signature' of plants is defined by the reflectance or absorption of electro-magnetic radiation in the visible, near-infrared (NIR) and short-wave infrared (SWIR) wavebands. The 'signature' is formed when the intensity of light energy coming from the plant is plotted over a range of wavelengths; the connected points produce a curve hence its spectral 'signature' (Figure 2). Plants have generally low reflectance in the visible region and high reflectance in the NIR and lower reflectance in the SWIR. However, while this typical 'signature' is characteristic of healthy leaves and canopies, the spectral reflectance of plants can vary considerably depending upon a wide range of factors.

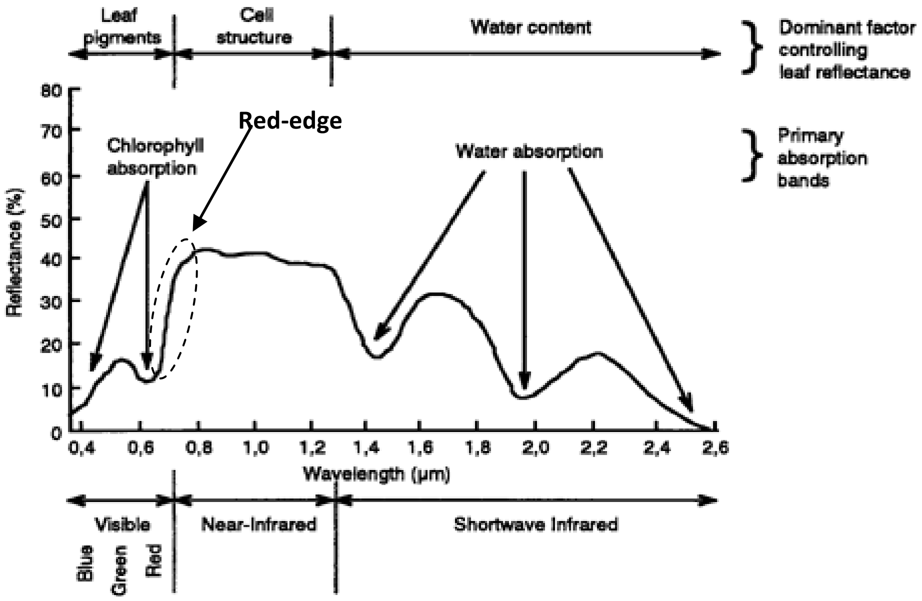

Figure 2. Typical reflectance characteristics of leaves. Adapted from Hoffer (1978).

Leaf reflectance in the visible region is predominantly influenced by chlorophylls and, to a varying extent, other photosynthetic and photoprotective pigments (Woolley, 1971; Wessman, 1990; Volgelmann, 1993; Ustin, *et al.*, 1999, 2004; Asner, 2004; Baltzer and Thomas, 2005; Liew *et al.*, 2008). These pigments absorb light strongly in the visible wavelengths and thus create low reflectance. In the NIR and SWIR, leaf cell structure (Slaton *et al.*, 2001) and water content in the tissues (Buschmann and Lichtenthaler, 1988) are the dominant factors, respectively. Chlorophylls which are of two forms (chlorophyll *a* and *b*) have a dominant control upon the amount of solar radiation that a leaf absorbs (Smith, 2002b; Blackburn, 2007). Most pigments absorb in the blue region centered around 445 nm but only chlorophyll absorbs in the red centered around 645 nm (Gates *et al.*, 1965). There is high reflectance in the NIR due to light scattering of the leaf cell structure and non absorption of chlorophylls. The structure of the leaf, with many air-water interfaces, makes a very strong scattering medium that causes high reflectance and transmittance in any region where absorbance is low (Woolley, 1971). A summary of the major features responsible for absorption/ reflectance of certain wavelengths that has been derived from Berry and Ritter (1997), Zwiggelaar (1998), Smith (2002a), Blackburn (2007) is given in Table 1.

Table 1. Absorption features of plant spectra.

Controlling factor	Waveband/wavelengths (nm)	Spectral effect
Chlorophyll a	435, 670-680, 740	Strong absorption
Chlorophyll b	480, 600-650	Strong absorption
α-carotenoid	420, 440, 470	Strong absorption
ß-carotenoid	425, 450, 480	Strong absorption
anthocyanins	400-550	absorption
chlorophyll a & b	550	strong reflectance/weak absorption
lutein	425, 445, 475	absorption
violaxanthin	425, 450, 475	absorption
water	970	weak absorption
water, CO_2	1450, 1944	strong absorption
water, oxygen	760	strong absorption

Adapted from Zwiggelaar (1998), Smith (2002), Blackburn (2007).

4.2. Diagnostic indicators of oil-induced stress in plants

4.2.1.Visible reflectance. The visible region ranges from 0.4-0.7µm (400-700nm), which is an extremely small portion of the electromagnetic spectrum but this corresponds to the spectral sensitivity of the human eye. The blue, green and red colours are ascribed to the approximate ranges of 0.4-0.5µm (400-500nm), 0.5-0.6µm (500-600nm) and 0.6-0.7µm (600-700nm) respectively. Several studies have recorded that visible reflectance increases consistently in various plant species in response to stress induced by a range of different stressors (Carter and Miller, 1994; Carter *et al.*, 1996).

Spectral measurements by Smith *et al.* (2004a) showed that vegetation exposed to high concentrations of natural gas in the soil had significantly increased reflectance in the visible and decreased reflectance in the infrared. In response to a number of different stressors, plants exhibit a decrease in the production of chlorophyll and other biochemical constituents, which leads to a decrease in their absorption capacity and therefore an increase in reflectance in the visible region. Sensitivity analysis of leaf spectral reflectance to leaf characteristics performed by Ceccato *et al.* (2002) using the new version of the PROSPECT model (Jacquemoud, *et al.*, 2000) shows that chlorophyll content had a major influence (followed by leaf internal structure) over reflectance values between 400 and 710nm compared to other pigments.

As the visible region is characterized by high absorption coefficients for pigments, reflectance in this region is more sensitive to lower pigment concentrations. For example, Blackburn (1998a, 1998b) and Sari *et al.* (2005) noted that reflectance at wavelengths corresponding to the centre of the major absorption features are most sensitive to low pigment concentrations as found in early immature and later senescent leaves and canopies with low leaf area and canopy cover. An empirical study by Rosso *et al.* (2005) showed that highly contaminated plants reflected incident radiation in the deep absorption features of the visible spectrum such as 670nm.

4.2.2. Red-edge region. The region of the reflectance red-edge has been used as a means of identifying stress in plants. The red-edge adjoins the red end of the visible portion of the spectrum. It is an area where there is change in reflectance between wavelengths 690 and 750nm which characterises the boundary between dominance by the strong absorption of red light by chlorophyll and the high scattering of radiation in the leaf mesophyll (Smith *et al.*, 2004b). At this region, reflectance rises rapidly leading to a plateau of high reflectance in the near-infrared, where pigments no longer absorb radiation (Blackburn, 2007). Horler *et al.* (1983) also stated that the red-edge is the sharp rise in reflectance of green vegetation between 670 and 780nm.

There is further suggestion that the red-edge region of the spectrum is considered a unique parameter for detecting stress in plant. The reflectance of stressed plants often shows a shift of the 'red edge' position towards shorter wavelengths (Noomen *et al.*, 2003). Red-edge shifts measured in airborne imaging spectrometer data have been proposed useful to provide an early indicator of vegetation stress. Evidence is given in Rock *et al.* (1988) where a shift in red-edge towards the blue, of approximately 5nm was detected when measuring severe foliage stress on spruce trees due to air pollution. The shift which was attributed to decline in chlorophyll in the pine needles was detected before visual symptoms became apparent.

A small number of investigations have looked specifically at the effects of hydrocarbon pollution on the reflectance red-edge of vegetation. Investigations by Bammel and Birnie (1994) discovered a consistent and significant blue shift of the green peak and red trough positions of sagebrush spectra and concluded that the red-edge is the most reliable indicator of hydrocarbon-induced vegetation stress. A large body of literature exists that generally shows a decrease in chlorophyll in natural vegetation due to stress, resulting in a shift to shorter wavelength of the red-edge. However, spectroscopic analysis by Yang *et al.* (1999) showed that the red-edge position of wheat spectra taken from areas of well known hydrocarbon microseepage has shifted 7nm to longer wavelengths.

To explain the situation, it is important to note that it is generally accepted that the position and shift of the red-edge is related to leaf and canopy chlorophyll concentration. Hence, a decrease or increase in chlorophyll results in red-edge shift towards either the shorter or longer wavelengths, respectively. In the case of Yang *et al.* (1999), it was suspected that hydrocarbons might have served as nutrients during the short growing season of wheat, which however needs further investigation. Evidence from previous studies shows that red-edge inflection point (λp) (the peak in the first derivative of reflectance that can be used to describe changes due to stress) ranges between 700 and 745nm. Jago and Curran (1996) found two first derivative maxima within the red-edge with peaks at approximately 693 and 709nm, while studying grassland canopies at a site contaminated with oil. However, the potential for exploiting the position of these peaks and other red edge features such as the distance between the peaks, and the magnitude or area of the red edge for plant stress detection have not been explored.

4.2.3. NIR region. The NIR waveband ranges between 700 and about 1000nm. The region is characterised by high reflectance primarily due to light scattering by leaf tissue or cellular structure (Gausman *et al.*, 1970). Ceccato *et al.* (2002) found that the leaf internal structure accounts for 70-80% of reflectance variations in the NIR whereas the leaf dry matter accounts for the remaining variations (30-20%). Leaf reflectance is very high in the NIR at ~800nm (Lenk *et al.*, 2007) and a decrease of the reflectance at 800nm may be taken as an indicator of reduced aerial interspaces in the mesophyll of leaves under stress conditions (Gausman and Quisenberry, 1990; Buschmann *et al.*, 1991). A body of literature has recently been developed through experimental studies, which show substantial evidence of high and low reflectance in non-stressed and stressed plants respectively within this region (Noomen *et al.*, 2003; Kempeneers *et al.*, 2005; Rosso *et al.*, 2005; Smith *et al.*, 2005;). Within these empirical studies, different problems were simulated given different scenarios. These include utilisation of different types of plant species, which were subjected to a range of stressors including water and nitrogen stress, water logging, shading, gas and heavy metal at varying levels of contamination. A similarity within this range of studies lies in the use of a ground based sensor – the spectroradiometer to measure the spectral reflectance characteristics of the experimental plants.

Treating plants of *Salicornia virginicia* with two metals – cadmium and vanadium, at different levels of contamination, Rosso *et al.* (2005) found that reflectance differences in the near infrared (NIR) portion followed a similar progression as the symptom expression; in contrast to visible wavelengths, towards a reduction in reflectance with stress. A reduction in intercellular spaces produces less light scattering and less reflectance (Rosso *et al.*, 2005). Water stress influences reflectance in the NIR region because of changes in mesophyll structure (Bowman, 1989). However, leaf structural characteristics have more influence in NIR reflectance than at short wave infrared, whereas water content has a strong control on reflectance at short wave infrared (SWIR) (Woolley, 1971; Ceccato *et al.*, 2001). It is worth noting that absorption of radiation by water does not have a large direct influence on reflectance in the NIR but it does have an important indirect effect due to its influence on leaf cellular structure which varies considerably as water content varies. Further evidence had been given in Ustin *et al.* (1999) that NIR reflectance is strongly determined by the structural characteristics of leaf parenchyma, fractions of air spaces and air-water interfaces.

4.2.4. Shortwave infrared (SWIR) region. The SWIR ranges between 1300 and 2500 nm and is characterised by light absorption by the leaf water. Tucker, (1980) and Gausman, (1985) show that SWIR is heavily influenced by water in plant tissue. Bowman (1989) indicated that water stress influences reflectance at the SWIR region because of a reduction of water content. A study by Fourty and Baret (1997) showed that the wavelengths at 1530 and 1720nm seem to be most appropriate for assessing vegetation water. Also, the radiative transfer model PROSPECT (Jacquemoud *et al.*, 2000) as a function of chlorophyll a & b concentration, C_w, C_m, and N was very efficient for estimation of vegetation water content at leaf level. In an attempt to detect vegetation leaf water content using reflectance in the optical domain, Ceccato *et al.* (2001) found that parameters such as the Equivalent water thickness (C_w) are not the only parameters responsible for significant reflectance variations within the SWIR range. Other controlling factors include the internal structure (N) and the dry matter content (C_m). The N and C_m affect reflectance at wavelength range from 700 to 2500 nm, while C_w affects the wavelength range from 900 to 2500 nm. While C_w accounts for 86.7% of the reflectance variation in the SWIR, N and C_m account for only 5.8% and 7.5% respectively. Thus, the SWIR reflectance value alone is not suitable for retrieving vegetation water content at leaf scale. Although C_w is the dominant factor, the study suggests that combination of information from both NIR (820nm) and SWIR (1600nm) is necessary for accurate estimation of vegetation water content at leaf scale from optical observations.

Ceccato *et al.* (2001) explained several indices proposed to measure vegetation stress due to water stress such as Crop Water Stress Index (CWSI), the Stress Index (SI), and the Water Deficit Index (WDI). These indices assumed that differences between the air and surface temperatures were related to plant water content and to water stress. Other indices, such as the moisture stress indices that combine satellite-based information on the relationship between Normalised Difference Vegetation Index (NDVI), surface temperature, and air temperature, in association with production efficiency models, have been developed (Goetz *et al.*, 1999). These indices do not provide a very accurate way for estimation of water stress because vegetation status is not a direct measurement of water content and many species may show signs of reduced evapotranspiration without experiencing a reduction in water content (Ceccato *et al.*, 2001).

4.2.5. Spectral and derivative indices. Several researchers have developed a wide range of spectral indices and wavelength regions that are feasible in detecting stress in a wide range of plant species (Carter, 1994a; Tarpley *et al.*, 2000; Read *et al.*, 2002; Sims and Gamon, 2002; Smith *et al.*, 2005b; Campbell *et al.*, 2007). Spectral indices based on reflectance spectroscopy offer the possibility for estimation of leaf pigment content. The indices commonly use reflectance ratios derived from dividing leaf reflectance at stress-sensitive wavelengths by that at stress insensitive wavelengths (Liew *et al.*, 2008). The idea for using this approach is to eliminate the effects of leaf internal reflections and thus, provide stronger quantitative relationships with chlorophyll content (Carter and Miller, 1994). A diverse range of spectral indices that combine reflectance in wavebands of different spectral regions have been employed for plant stress detection and includes simple ratios of reflectance and normalised difference ratios.

For example, in studying plant spectral responses to gas leaks and other stresses, Smith *et al.* (2005) calculated a reflectance ratio by combining wavebands in the visible region near 560nm and 670nm. The study found that in contrast to the control or the shade-stressed plants, the ratio increased in gas- and herbicide-stressed plants. They suggested that an increase in the ratio $R_{670-680}/R_{555-565}$ could be used to detect plant stress caused by elevated natural gas in soils due to leaks. Tarpley *et al.* (2000) suggested that simple reflectance ratios that combine leaf reflectance values at 700nm or 716nm and 755-920nm could improve precision and accuracy in predicting cotton leaf nitrogen concentration. Read *et al.* (2002) found strong associations between leaf constituents such as chlorophyll, carotenoids and nitrogen and simple ratios of reflectance at the wavelengths

415/695nm, 415/685nm, and 415/710nm, respectively. They found that reflectance at waveband 415nm appeared to be a more stable spectral feature under nitrogen stress, as compared with more pronounced changes along the reflectance red edge at 630nm - 690nm.

Zhao *et al.* (2005) found high correlation between the reflectance ratios of R_{551}/R_{915} and R_{708}/R_{915} and chlorophyll concentrations in field-grown cotton. They also found the same relationship at a single wavelength of 551nm or 707nm and high linear correlation between nitrogen concentrations and a spectral reflectance ratio of R_{517}/R_{413}. Sims and Gamon (2002) enhanced spectral indices by incorporating waveband in the blue region to correct for specular reflectance. This resulted to more accurate estimation of leaf chlorophyll concentrations. Many other spectral indices derived not only from spectral reflectance but also from derivative spectroscopy have been found useful for studying plant damage. For example, derivatives ratios such as D_{715}/D_{705}, D_{REP}/D_{714}, D_{744}, D_{705}, or D_{745} (where D represents the amplitude of the first derivative at specific wavelength and D_{REP} is the amplitude of the first derivative at the wavelength of the maximum amplitude in the red edge region) were sensitive to stress and reflect the differences in the shape of the first derivative curve among damage levels (Entcheva, 2000). In their experimental study, Campbell *et al.* (2007) found that D_{715}/D_{705} consistently performed well as they exhibited high values for the unstressed condition and significantly lower values as vegetation stress increased.

From the foregoing discussion, it is clear that change in plant reflectance spectra at specific regions, red-edge features, ratios of narrowband reflectance and derivatives are valuable indicators of stress. However, the optimal index to monitor plant stress response to oil pollution is not known. Besides, the potentials of other red-edge features such as the position of the double features, the distance between them and the magnitude or area of the red-edge for plant stress detection have not fully been explored. Thus, this study suggests that the potential of these diagnostic indicators of plant stress be further investigated.

5. Optical remote sensing techniques

Optical remote sensing techniques use data from sensors that collect radiation in the reflected solar spectrum (about 350 to 2500nm). Optical remote sensing instruments can be operated from different platforms such as ground-based, air-borne or space-borne, each with various strengths and weaknesses. Basically, at field and laboratory scales, the methodology or approach that could be applied at a larger scale for various plant stress monitoring applications could be developed. For example, a variety of narrow band spectral reflectance features have been shown to be related to changes in vegetation condition and amount through laboratory and field studies (Treitz and Howarth, 1999). In addition, results from laboratory scale studies can provide the basis for operational applications of vegetation stress monitoring. However, aside from scale or platform definitions, optical remote sensing for vegetation stress monitoring has been more commonly categorized according to spectral resolution.

5.1. Multispectral and hyperspectral remote sensing

Multispectral sensors collect data in a few broad spectral bands that cover important regions of the reflected solar spectrum and have been applied for a wide variety of environmental applications (Okin and Roberts, 2004). Van Der Meer *et al.* (2002) noted that the laboratory and field scale spectra of vegetation stress have been studied in detail, but the resolution of broad-band instruments such as the Landsat Thematic Mapper (TM) or Multispectral Scanner (MSS) is not sufficiently high for comparison with laboratory or field spectra. This means that the broad bandwidth cannot characterize all the absorption features that respond to vegetation stress, regardless of the type of enhancements employed or the type of information extraction method applied (Van Der Meer *et al.*, 2002). For this reason, a frequent use of multispectral remote sensing systems is with vegetation indices.

Van Der Meer *et al.* (2002) note that vegetation indices are quantitative measurements, based on digital values, which attempt to measure biomass or vegetative vigour and the most popular and widely used is NDVI. The index combines two channels in a ratio or difference i.e. (NIR-RED)/(NIR+RED) which allows response to vegetation growth to be distinguished from the background signals. Some of the inherent limitations associated with NDVI are adequately provided in Okin and Roberts (2004) and Van Der Meer *et al.* (2002). For vegetated landscapes, attention has been directed towards increased spectral sampling because of great spectral variability, in the 0.7μm to 2.5μm range (Curran, 2001). A detailed description of the band-ratio strategy is given in Van Der Meer *et al.* (2002).

Multispectral sensors feature a combination of limited number of spectral bands with planes, helicopters or satellites as their platforms. With satellites, it is possible to acquire high spatial resolution images at a very wide coverage and on regular basis which makes it cost effective. However, satellite data are known to be adversely affected by cloud cover, atmospheric attenuation and scattering which necessitate some corrections. In addition, fixed satellite orbits impose some limitations as they create inflexibility in timing of data acquisition. For example, when high cloud cover for a given region coincides with time the satellite orbits that region, it will be impossible to acquire clear images for that region. The visible and infrared regions are affected in particular and are very critical for vegetation monitoring. Hence, satellite-based multispectral systems have been proved very useful in regions where there are relatively clear skies, but can be very limited in regions with frequent cloud cover. Using data from a feasibility study from 1990, Steven *et al.* (1997) found that in UK, the number of days with less than 2 oktas cloud cover between June and September sampled by the SPOT (orbiting 11 times every 26 days) and Landsat (orbiting once every 16 days), systems were between 2 and 9 days.

Multispectral remote sensing technologies have well-known applications in vegetation studies, for example in the mapping of physical and structural features of vegetative ecosystems and in forest surveys (Treitz and Howarth, 1999). In addition, it has offered opportunity for successful monitoring of deforestation and desertification through quantification and estimation of vegetative ecosystems. With multispectral remote sensing such as the Landsat Thematic Mapper, it is possible to quantify vegetation biophysical properties such as Leaf Area Index (LAI) using spectral indices derived from their broad wavebands (Asner, 1998; Treitz and Howarth, 1999; Blackburn, 2007). Table 2.2 illustrates some characteristics of airborne and spaceborne multispectral systems.

The main advantage of airborne remote sensing is that the effects of cloud cover, atmospheric attenuation and scattering can be controlled or avoided. Data can be acquired when the skies are clear and at any desired temporal frequency on a repetitive basis thus, leading to a cost effective means of monitoring the environment. The system provides several advantages over satellite systems as they are simple, reliable and inexpensive (Campbell, 1996). However, airborne systems have a more limited spatial coverage than satellite systems, which offer the potential of complete global coverage. In addition, there are inherent risks associated with low level flights required for monitoring leaks from oil pipeline as the accuracy of information depends solely on the pilot.

However, the major consideration in the choice of appropriate remote sensing system for vegetation stress monitoring is the spectral resolution. As information about the general health status of vegetation is often embedded in narrow spectral features, a high spectral resolution is required. The spectral resolution, which is the ability of a sensor to resolve spectral features, is controlled by the bandwidth, spectral sampling interval and number of bands. In principle, the higher the spectral resolution, the greater the chances of gathering useful information for better understanding of plant health status. Biochemical constituents relate to and invariably provide accurate information about physiological characteristics and thus, allow assessment of vegetation condition. Many biochemicals have fine spectral features which cannot be sampled using the broad bandwidths of some optical remote sensing systems (Clark, 1999; Yang *et al.*, 2000; Curran, 2001). This is because they use average spectral information over broadband widths resulting in loss of critical information available in specific narrow bands (Blackburn, 1998; Thenkabail *et al.*, 2000). Overall, it is clear how spectral resolution can be important in determining the ability of a remote sensing system to monitor vegetation stress.

Spatial resolution specifies the smallest object that could be detected by a sensor. There are several remote sensing systems of very high spatial resolution of 1m or less but they have a limited spectral resolution. High spatial resolution data have primary applications in managing forest inventory related to assessing stock levels and classification of vegetation types (Wulder, 1998; Wulder *et al.*, 2000). Indeed high spatial resolution data are extremely useful for refining stress detection methods by allowing us to discriminate between different vegetation types and therefore constrain our predictions. However, there is growing evidence that for mapping of vegetation condition associated with health and nutrition, and biological invasion (pest, diseases, and weeds), a sensor that can measure in several hundreds of narrow bands is required, usually with a bandwidth of 10nm or less (Filella and Peňuelas, 1994; Bronge and Mortensen, 2002; Liew *et al.*, 2008). Unfortunately, due to technical constraints, satellite remote sensing systems are unable to offer both high spatial and high spectral resolution but airborne systems do have this capacity.

In reviewing hyperspectral techniques for estimating biophysical parameters of forest ecosystems, Treitz and Howarth (1999) provide characteristics of several imaging spectrometers that can acquire contiguous spectra over land and water surfaces. These are presented in Table 2.

Table 2. Characteristics of selected hyperspectral imaging spectrometers.

Sensor	No. of bands	Spectral coverage (nm)	Spatial resolution (m)	Band width (nm)	Period of operation	Platform
CASI	288	385-905	25cm-1.5m	10	since 1989	Airborne
AVIRIS	224	380-2500	20m	9.4-16.0	since 1987	Airborne
SFSI	240	1200-2400	4	10	since 1994	Airborne
Probe-1	128	400-2450	1-10m	Nov-18	since 1994	Airborne

Hymap	126	50-2500	03-Oct	15-20	since 1999	Airborne
Hyperion	242	400-2500	30	10	since 2000	Space-borne

CASI – Compact Airborne Spectrographic Imager
AVIRIS – Airborne Visible Infrared Imaging Spectrometer
SFSI – Shortwave Infrared Full Spectrum Imager
(Adapted from NERC Earth Observation data centre and Treitz and Howarth, 1999)

6. Synthetic Aperture Radar (SAR) imaging techniques

Radars are active sensors which operate in the microwave region of the electromagnetic spectrum (wavelengths in the order of millimeters to centimeters). SAR imaging has potential for large area coverage and is noted to have all weather and cloud cover penetration capabilities, and thus, is valuable in areas that are prone to frequent cloud cover. The European Space Agency (ESA) (2007) indicates that the microwave capability offered by the ERS series means that observation is not limited by weather or light conditions as are optical data. The agency provides an overview of the wide range of applications of Earth Resources Satellite (ERS) SAR data. These ranges of practical application of the earth observation system have been classified under oceanic and land environments and have also been noted as an emergency application technique.

For example, on the oceans, most of the illegal or accidental anthropogenic spills, as well as natural seepage from oil deposits, are clearly visible on radar images. Ships can be detected and tracked from their wakes. Ice monitoring, mapping of the topography of the ocean floor and provision of input data (such as ocean waves and their direction of displacement) for wave forecasting and marine climatology are achievable. Major areas of application of SAR images include:

- (i) mapping and monitoring landuse/landcover and for forestry changes and agriculture studies for monitoring crop development.
- (ii) enhancement of geological or geomorphological features.
- (iii) supports georeferencing of other satellite imagery to high precision, and in regular updating of thematic maps.
- (iv) helps to optimize response initiatives and assess damages after flooding.
- (v) interferometric SAR can be used under suitable conditions, to derive elevation models or to detect small surface movements, in the order of a few centimeters, caused by earthquakes, landslides or glacier advancement.

Monitoring the scale of global crop production and trade has been identified as an area in which SAR data may be able to assist. In addition, these systems provide information for mapping forest extent and type, particularly in tropical areas which have not previously been mapped due to almost continuous cloud cover. It is a unique source of data, and in conjunction with other remotely sensed data it can be used to map forest damage, the encroachment of agriculture onto forested areas unsuitable for development, and in general to provide inventories of timber areas. It is worth noting that despite many advantages of SAR system, it has some inherent limitations especially in the context of vegetation stress monitoring. There is a lack of evidence that it can be used in this context as many of the available microwave sensors lack spatial resolution to be practical for plant stress monitoring. They are more responsive to change in vegetation structure than function thus, can only be of relevance for severe or later stages of stress especially when plant death must have occurred.

7. Lidar imaging techniques

One emerging technology that is gaining rapid attention in remote sensing of vegetation particularly at canopy scale is LiDAR (Light Detection and Ranging). LiDAR is an active system; based on an artificial radiation source that operates in the near-infrared. Vegetation has high reflectance and transmittance at this region; allowing a strong return from the forest canopy as well as from the forest floor (Kasischke *et al.*, 2004). The technology provides horizontal and vertical information at high spatial resolutions and vertical accuracies (Lim *et al.*, 2003). LiDAR has the capability of measuring the geometrical structure of plants which is the most important factor that influences the reflectance of plants at canopy scale. For example, Riano *et al.* (2004) demonstrated the possibility of measuring canopy LAI from LiDAR imagery.

Thus, while LiDAR imagery alone is probably insufficient for monitoring plant stress, its combination with hyperspectral imagery is very promising, in this respect. For example, one notable area of LiDAR data application which has improved the accuracy of pigment estimates at the stand scale is in extraction of spectral information from tree crowns, while extraneous spectral information from canopy gaps are removed (Blackburn, 2002). The study noted that this was possible by applying spatial filters created from the canopy surface elevation models derived from the LiDAR data to imaging spectrometer data from forests. Again, with imaging LiDAR, it is possible to quantify total canopy chlorophyll content; by using the measured canopy LAI to scale-up estimates of foliar chlorophyll concentration derived from hyperspectral data (Solberg *et al.*, 2005). Blackburn (2007) suggests that the combination of LiDAR and hyperspectral imaging technique in studying the geometrical structure of heterogeneous canopies remain a possibility which needs further investigation.

8. Conclusion

Plant stress can be caused by various biotic and abiotic factors. Oil pollution is an abiotic factor that can affect plants. Plants can be affected directly through physical contamination with oil or indirectly through soil pollution. Various remote sensing techniques have been identified as valuable tools for estimating and mapping plant biochemical and biophysical properties, in order to understand the health status of plants.

In the context of hyperspectral remote sensing, several approaches have been found to be useful for plant stress detection both at early and later stages. These include: the use of characteristics of spectral reflectance in the visible, NIR and SWIR regions, the characteristics of the red edge such as the position, selection of diagnostic individual narrow wavebands, and a plethora of spectral reflectance- and derivative-based ratios. However, the optimal spectral indicator for monitoring plant stress induced by oil pollution is not known. In summary, there is strong evidence that hyperspectral remote sensing techniques hold considerable potential for monitoring plant stress, but the specific case of determining the optimal index for detecting and quantifying stress induced by oil pollution requires further investigation.

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