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Detecting the effects of hydrocarbon pollution in the Amazon forest using hyperspectral satellite images

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ABSTRACT

The global demand for fossil energy is triggering oil exploration and production projects in remote areas of the world. During the last few decades hydrocarbon production has caused pollution in the Amazon forest inflicting considerable environmental impact. Until now it is not clear how hydrocarbon pollution affects the health of the tropical forest flora. During a field campaign in polluted and pristine forest, more than 1100 leaf samples were collected and analysed for biophysical and biochemical parameters. The results revealed that tropical forests exposed to hydrocarbon pollution show reduced levels of chlorophyll content, higher levels of foliar water content and leaf structural changes. In order to map this impact over wider geographical areas, vegetation indices were applied to hyperspectral Hyperion satellite imagery. Three vegetation indices (SR, NDVI and $NDVI_{705}$) were found to be the most appropriate indices to detect the effects of petroleum pollution in the Amazon forest.

1. Introduction

Global demand for energy is trigging oil and gas exploration and production across the Amazon basin, with even very remote areas leased out or under negotiation for access (Finer et al., 2008). In western Amazonia, there has been an unprecedented rise in this activity, causing environmental pollution in vast regions of forest via oil spills from pipelines networks and leakages from unlined open pits (Hurtig and San-Sebastián, 2005; Bernal, 2011).

In some cases this has led to legal actions by local residents against international oil companies (Bernal, 2011; Rochlin, 2011). Currently in Ecuador, the petroleum industry and its environmental/social interactions are at the centre of controversy since very sensitive regions and protected areas of this Amazon forest are under exploration and production (Marx, 2010; Martin, 2011; Vallejo et al., 2015).

Despite high international public interest in protecting Amazon rainforests, little scientific attention has focussed on the effects of oil pollution on the forest; much focus is on threats from deforestation, selective logging, hunting, fire and global and regional climate variations (Asner et al., 2004; Malhi et al., 2008; Davidson et al., 2012). The high diversity and intrinsic complex biological interactions of tropical forests and their vast expanse challenge our understanding of the impact of oil on them. Data collected *in situ* in these forests are rare, most likely due to access issues. An alternative approach to measuring and monitoring oil contamination in tropical forests at suitable spatial and temporal scales is desirable. It is suggested here that satellite imaging spectrometry, which affords the collection of hyperspectral data of the environment, could be a way forward. In order to detect vegetated landscape contamination using imaging spectrometry, environmental change as a result of contamination need to have a measurable impact upon the biochemical, and related biophysical properties (e.g., pigment concentration, leaf structural and leaf area), of the vegetation growing in that environment. Such properties measured using hyperspectral remotely sensed data may then be used as a proxy to contamination (Mutanga et al., 2004).

Experimental data generated under controlled conditions have demonstrated that plants exposed to pollutants exhibit stress symptoms (Horvitz, 1982, 1985; Smith et al., 2005a) which manifest themselves primarily in lower levels of chlorophyll content. Stress levels do, however, depend on plant tolerance to both

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concentration and exposure period (Smith et al., 2005b; Noomen et al., 2006). There is now an increasing availability of hyperspectral remotely sensed data from space (Hyperion on board of Earth Observation EO-1; Compact High Resolution Imaging Spectrometer-CHRIS on board of PROBA-1) and more are imminent at the time of writing (e.g., Sentinel-2; Environmental Mapping and Analysis Program (EnMAP)). The development of techniques to utilise these data sets for the detection of specific pollutants in a tropical forest environment is necessary and forms the focus of this study. Approaches to using these data include the use of both broad- and narrow-band vegetation indices (e.g., (Blackburn, 2007)) and red edge position location (e.g., (Dawson and Curran, 1998)). Their success may vary between species and pollutant (Steven et al., 1990; Sims and Gamon, 2002), however, previously these techniques have been used to detect vegetation contamination by heavy metals (Kooistra et al., 2003; Rosso et al., 2005), radioactive materials (Davids and Tyler, 2003; Boyd et al., 2006), as well as hydrocarbons (Smith et al., 2005b; Jago et al., 1999; Noomen et al., 2008; Noomen and Skidmore, 2009; Zhu et al., 2013) and herbicides (Dash and Curran, 2006).

1.1. *Vegetation stress caused by crude oil*

Vegetation responds to stress conditions with long-term metabolic and morphological changes: these include changes in the rate of photosynthesis, changes in the absolute and relative concentration of the photosynthetic pigment (chlorophyll a and b, carotenoids) and changes in leaf size, thickness and structure (Davids and Tyler, 2003). Different plant species respond differently to a particular stressor. Furthermore, the nature, intensity and length to exposure are factors that define the stress level on the vegetation. Baker (1970) summarised several pieces of research related to the effects of crude-oil on plants and showed that the toxicity of petroleum oil depends on the concentration of unsaturated, aromatics and acids compounds: the higher their concentration, the more toxic the oil is for plants. Molecules of crude-oil can penetrate the plant through its leaf tissue, stomata, and roots. The rate of penetration depends on the oil type, the contact part (leaves, roots), time of exposure, thickness of the cuticle and the density of the stomata. After penetrating into the plant, the oil may travel into the intercellular space and possibly also into the vascular system. Cell membranes are damaged by the penetration of hydrocarbon molecules leading to the leakage of cell contents, and the possible entry of oil into the cells.

Plant transpiration, respiration and photosynthetic rates are affected by hydrocarbon pollution (Baker, 1970). The effects of hydrocarbons in plants reduce plant transpiration rates. On the other hand, plant respiration may either decrease or increase depending on the plant species or the oil type. Hydrocarbons reduce the rate of photosynthesis, and the amount of reduction varies with the type and amount of oil and with the species of plant. Cell injury may be the principal cause of photosynthesis inhibition because hydrocarbons tend to accumulate in the chloroplasts, which explains the reduced levels of chlorophyll content in vegetation affected by hydrocarbons.

1.2. *Vegetation stress and chlorophyll*

The interaction between hydrocarbons and the soils reduces the amount of oxygen and increases the CO_2 concentration, soils turn acidic and minerals are mobilised. These changes affect the vegetation health (Noomen et al., 2006; Shumacher, 1996; Yang, 1999; van der Meer et al., 2006). Controlled experiments in the laboratory, most of them being applied to crops, have demonstrated that plants exposed to hydrocarbons experience reduced levels of chlorophyll which is a key parameter to detect plant stress caused by hydrocarbons (Smith et al., 2005a,b; Noomen and Skidmore, 2009; Yang, 1999; Smith et al., 2004a,b; Noomen, 2007). It is not clear how hydrocarbons influence changes in biophysical and biochemical parameters of vegetation growing in natural environments. At present, there published studies that investigate the effects of hydrocarbons in vegetation of tropical forest in the Amazon region.

This paper demonstrates the suitability of satellite imaging spectrometry for the detection of contamination by oil of the forest in the Ecuadorian Amazon. EO-1 (Earth-Observation 1) Hyperion imagery is analysed with supporting field data on soils and foliar properties with an overriding objective of producing a map of the spatial pattern of forest contamination by oil.

2. Materials and methods

2.1. *Study area and sites*

Three study sites within Ecuadorian Amazon rainforest were investigated (Fig. 1). Two were located in the lowland evergreen secondary forest of Sucumbios province, in the Tarapoa region (0°11′ S, 76°20′ W). Due to their close proximity, both sites share soil types, weather and anthropogenic influences. Site 1 (polluted) is located by an abandoned petroleum platform where open pits have been discharging crude oil to the environment, or leaching out as the pits degrade or overflow, for the past 15 years. Site 2 (non-polluted) is some distance from Site 1 and so not directly influenced by the oil pollution evident at Site 1. Site 3 (Pristine forest-Yasuni) is situated in the highly diverse lowland evergreen primary forest of the Orellana province, in the northern section of Ecuador's Yasuni National Park (0°41′ S, 76°24′ W). The forest has a species richness among the highest globally (Tedersoo et al., 2010) and are situated well away from any sources of crude oil (and other anthropogenic influences).

2.2. *Site sampling and measurements*

Fieldwork was undertaken from April to July 2012. From each of the three sites two sets of data were collected to measure any oil presence and potential contamination. One set focused on the measurement of levels of oil in the soil. Eight soil samples, randomly situated, were collected at each of the three sites and several parameters related to physical properties, nutrients, metals and hydrocarbons traces were analysed in accredited laboratories following international standard methods (see Annex 1 for details of soil sampling and results). The other set of data focused on measuring the foliar biochemistry of leaves from the trees located at each site. At Site 1 all trees located around the source of oil were sampled (388 samples); at Site 2 selectively sampled areas located between 400 and 1250 m from Site 1 were the focus of measurement (124 samples); and in Site 3 accessible trees were sampled from 12 parcels of 20 × 20 m which covered an area of 4800 m^2 (545 samples). In total, therefore 1057 trees were sampled (see Annex 2 and Annex 3 for a detailed description of the plant family and specie sampled). From each tree well-developed branches, acquired from different levels of the vertical forest profile using a telescopic pruner, tree-climbing techniques and canopy towers, were sealed in large polyethylene bags and stored in ice coolers.

Fully expanded mature leaves, with no herbivorous/pathogenic damage, were selected from each of the collected branches and analysed. Each leaf was clipped at the midpoint using cork borers to obtain a disk of known surface *(S)*; this is the optimal position from which to take chlorophyll readings (Hoel, 1998). Three SPAD-502 chlorophyll meter readings were taken from each disk, at