REMOTE SENSING OF OIL IN VEGETATED REGIONS: AN OVERVIEW OF RECENT ADVANCES AND FUTURE CHALLENGES TOWARD OPERATIONAL APPLICATIONS

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ABSTRACT

This brief review focuses on the use of optical remote sensing for oil prospecting and monitoring in vegetated regions. Major advances have been achieved in this field during the last decade. Recent studies demonstrated that oil can be detected and quantified by exploiting vegetation reflectance from airborne- and satellite-embedded sensors. Various methods coupling vegetation indices or radiative transfer models with classification or regression algorithms have been proposed for this purpose. High spatial and spectral resolutions greatly increase the accuracy of oil detection and quantification. However, important limits remain in regions with sparse or highly diversified vegetation. Oil spills become also more difficult to map when other environmental stressors occur. Hence, an important effort remains to move toward operational applications, especially on upcoming drone- and satellite-embedded hyperspectral sensors.

***Index Terms*—** hyperspectral remote sensing, soil contamination, oil, vegetation, reflectance

1. INTRODUCTION

In oil and gas industry, oil spill events can occur at every step of the production process in the onshore environment, leading to soil contamination and heavy ecological consequences [1]. To prevent from this, multi- and hyperspectral remote sensing has been used in oil monitoring over the last decades. Likewise, oil mapping is important for prospecting natural seepages. Although encouraging perspectives of operational applications have emerged in this field, important limits remain in vegetated regions. Indeed, oil cannot be detected directly by optical remote sensing when masked by vegetation. However, the unfavorable growing conditions provided by oil may affect plant biochemistry and optical properties [2]. This suggests being able to monitor oil indirectly by multi- and hyperspectral imagery. Various methods have been developed for this purpose recently, making possible to detect and quantify oil accurately from airborne- and satellite-embedded sensors [3], [4]. To succeed, these methods imply that the specifications of the sensor (*e.g.* the spatial and spectral resolutions) comply with those needed to track changes in plant reflectance induced by oil. This approach sparked a growing attention in the last 10 years. Since then, the development of drone- and satellite-embedded hyperspectral sensors is encouraging oil and gas companies to make remote sensing an operational tool for monitoring oil contamination in vegetated regions. This short review aims at summarizing the last advances and future challenges in this field.

2. OVERVIEW OF RECENT ADVANCES

During the last decade, several studies have aimed to map oil by exploiting vegetation reflectance measured by multi- and hyperspectral sensors (Table 1). This approach was tested on a wide diversity of vegetation types from various regions. Most of the studies focused on mapping oil spills, whereas a few attempted to detect natural seepages and contaminated mud pits. The use of vegetation indices is the most common way to achieve this. For instance, Ozigis *et al.* [5] detected oil spills with 70% accuracy by combining 10 indices in classification on Landsat-8 images. In the Amazon forest, Arellano *et al.* [1] applied successive index thresholds to map oil-induced stress near production facilities using Hyperion images.

Table 1. Overview of remote sensing of oil in vegetated regions using airborne and satellite multi- and hyperspectral imagery. (RTM: Radiative Transfer Model.)

Vegetation	Target	Sensor	Sensor type (resolution)	Bands	Method	Ref.
Mangrove	Oil spill	Landsat-8	Satellite (30 m)	9	Indices + Mean comparison	[6]
Crops, grassland, trees	Oil spill	Landsat-8	Satellite (30 m)	9	Indices + Classification	[5]
Mangrove	Oil spill	Landsat-5 & -7	Satellite (30 m)	6	Indices + Regression	[7]
Mangrove	Oil spill	Landsat-5 & -7	Satellite (30 m)	6	Indices + Mean comparison	[7]
Wetland	Oil spill	AISA	Airborne (1.5 m)	286	Reflectance + Classification	[8]
Crops	Gas spill	HyMap	Airborne (4 m)	128	Indices + Spatial filter	[9]
Shrubs	Mud pit	HySpex	Airborne (1 m)	409	Indices; RTM + Classification; Regression	[3]
Crops	Seepage	CASI – SASI	Airborne (1–2.5 m)	149	*Continuum* removal; RTM + Regression	[10]
Grassland	Seepage	Probe-1	Airborne (8 m)	128	Indices + Spatial filter	[4]
Tropical forest	Oil spill	Hyperion	Satellite (30 m)	242	Indices + Threshold	[1]
Plain & rainforest	Oil spill	Hyperion	Satellite (30 m)	242	*Continuum* removal; indices + Mean comparison	[11]

Other methods are based on retrieving leaf biochemistry by inverting radiative transfer models to track alterations in pigment contents, which are relevant indicators of oil exposure [10]. In a recent study, the chlorophyll content of shrubby vegetation estimated from airborne imagery allowed quantifying oil concentration in soils [3].

Because vegetation reflectance is affected by multiple factors, false alarms appear when mapping oil spills from airborne and satellite imagery [1], [4]. They come mostly from vegetation stress not induced by oil (*e.g.* drought, nutrient deficiency), and makes the detection very challenging. High spatial resolution imagery is a first solution to tackle these false alarms. Likewise, high spectral resolution helps tracking changes specifically induced by oil and discriminating them from other stressors. Although no current satellite-embedded sensor offers high spatial and spectral resolutions simultaneously at this stage, airborne- and drone-embedded sensors are good alternatives. However, mapping spills becomes very difficult in regions with species that do not share the same sensitivity to oil. It has been shown that a species exposed to oil may exhibit the same spectral signature than that of a non-exposed one [12]. This might affect the accuracy of the mapping at low and medium spatial resolutions, because several species are mixed in pixels.

Judging by the above-mentioned studies, the development of methods for mapping oil implies a good knowledge about the context. Experiments carried out under controlled conditions (*e.g.* under greenhouse) greatly help achieving this, provided that they are representative of the field [2], [13], [14]. These experiments aim at characterizing the effects specifically induced by oil on vegetation. They proved useful in developing methods intended to be applied to airborne and satellite imagery. Upscaling these methods from leaf to canopy scale and then on images is not an easy task, but vegetation indices and radiative transfer models are adapted to this purpose. Following a multiscale approach (leaf – canopy – images), Lassalle *et al.* [3] succeeded in detecting and quantifying oil in mud pits from airborne hyperspectral images (accuracy > 90%).

Therefore, the feasibility of monitoring oil in vegetated regions using optical remote sensing is no longer to be demonstrated. However, the methods listed in Table 1 were assessed locally, in a specific region. To move toward operational use, they should be tested in a wide range of contexts faced in oil and gas industry (e.g. pipeline and storage tank spills), in various regions (temperate, tropical, etc.). This requires extending the scope of existing methods and overcoming their limits. In addition, they should be adapted to the specifications of future satellite-embedded sensors.

2. PERSPECTIVES OF APPLICATION

To support oil activities in vegetated regions, remote sensing must make it possible to map seepages and spills over large areas. To date, the existing methods achieve it locally, on a specific site, which limits their operational application. The detection and quantification of oil based on vegetation indices and radiative transfer models perform well for a given vegetation type (Table 1), which location is known. In an operational frame, these methods could serve for mapping new seepages and spills over unknown areas. However, the same vegetation type must be established on the area to achieve accurate mapping. Thus, one way

to extend the scope of existing methods would be to assess their performance for different vegetation types [12], [15], [16]. To apply them operationally over large areas, satellite imagery is recommended. Although airborne-embedded sensors offer better spatial resolutions, satellite imagery can provide images on a weekly to daily frequency [1], [11]. This is mandatory for monitoring industrial facilities continuously. However, the best spatial resolution of current and future satellite-embedded hyperspectral sensors is 8 m. In contrast, the best methods for mapping oil were developed on airborne imagery with high spatial resolution (≤ 4 m). So, to use these methods operationally, it is necessary to adapt them to lower spatial resolutions. Conversely, drone-embedded hyperspectral sensors provide images with very high – up to centimetric – spatial resolution. They do not cover very large areas, but they can be deployed at any time by field operators. Although drone remote sensing is still under development, it shows great perspectives of application for oil and gas companies.

As highlighted above, the detection of oil at large scale remains difficult without knowing the vegetation types present on the sites. As a first step, an automatic mapping of the different vegetation types would reduce the risk of false alarms due to applying the methods on irrelevant vegetation types [3]. This mapping can be very difficult in regions with high plant diversity, especially using satellite imagery. Spectral unmixing might help achieving this. It proved efficient in mapping species, so it could serve prior to detecting oil. Thanks to very high spatial resolution, drone imagery might also help identifying the vegetation types of interest on the sites.

Apart from the vegetation type, the accuracy of oil detection is largely influenced by its concentration in soils. High concentrations lead to marked changes in plant reflectance, which are easy to catch by satellite and drone imagery [1], [12], [14]. The methods listed in Table 1 have each been tested for a certain level of oil in soil. However, their range of effectiveness is yet to be determined. This is essential for operational use, because oil contamination can extend to a large range of concentrations. Species that differ in sensitivity to oil could serve for detecting and quantifying oil in various ranges of concentrations, as suggested by recent studies. However, a single pixel of satellite images is likely to include vegetation exposed to different levels of contamination, making oil detection and quantification challenging. Once again, drone imagery might improve the accuracy of oil mapping.

At this stage, the use of optical remote sensing for mapping oil in vegetated regions has been mainly assessed on major spill and microseepage cases (Table 1). In an operational perspective, it should be tested in other contexts, including chronic pipeline and storage tank leakages, costal contamination, etc. Oil is not difficult to detect when spreading in high quantities over large areas, but frequently, leakages occur in a diffuse way over a few square meters [9], [17]. This can make the detection difficult when using satellite imagery, as pixels might include both healthy and oil-exposed vegetation. The very high spatial resolution provided by drone-embedded sensors might be helpful in that situation. For example, the methods of oil detection could be assessed for detecting chronic leakages along pipeline routes, by coupling satellite and drone imagery.

4. CONCLUSION

This brief review aimed at summarizing the last advances and challenges in using optical remote sensing for mapping oil in vegetated regions. Although significant progress has been made in this field during the last decade, further research is needed to operationalize the methods of oil spill and seepage detection proposed in the literature. Promising perspectives of satellite and drone applications opened in previous studies should be addressed in future research.

5. AKNOWLEDGEMENTS

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6. REFERENCES

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