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Hyperspectral sensing of heavy metals in soil and vegetation: Feasibility and challenges

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A B S T R A C T

Remote sensing of heavy metal contamination of soils has been widely studied. These studies concentrate heavily on the hyperspectral reflectance of typical metals in soils and in plants measured either *in situ* or in the laboratory. The most used wavebands lie within the visible-near infrared portion of the spectrum, especially the red edge. In comparison, mid- and far-infrared wavelengths are used far less frequently. Hyperspectral data are optimized to suppress noises and enhance the signal of the targeted metals through spectral derivatives and vegetation indexing. It is found that only subtle disparity exists in spectral responses for some metals at a sufficiently high content level. Not all metals have their own unique spectral response. Their detection has to rely on their co-variation with the spectrally responsive metals or organic matter in the soils. The closeness of the correlation dictates the accuracy of prediction. Without any theoretical grounding, this correlation is site-specific. Various analytical methods, including stepwise multi-linear regression, partial least squares regression, and neural networks have been used to model metal content level from the identified spectrally sensitive bands and/or their transformed indices. Both the model and the explanatory variables vary with the metal under detection and the area from which *in situ* samples are collected. Despite the amply demonstrated feasibility of estimating several metals by a large number of authors, only a few have succeeded in mapping the spatial distribution of metals from HyMAP, HJ-1A and Hyperion images to a satisfactory accuracy using complex algorithms and after taking environmental variables into account. The large number of reported failures testifies the difficulty in the detection of heavy metals in soils and plants, especially when their concentration level is low. The reasons or factors responsible for the success or failure have not been systematically analyzed, including the minimal spectral resolution required.

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1. Introduction

Heavy metals in soils are one of the most hazardous pollutants in the environment owing to their toxicity, persistency, easy uptake by plants and long biological half-life. They can destroy the normal functioning of soils, cause stress to crops, and impede their growth. If absorbed by crops, they can also enter the food chain and harm human health. There is no precise definition as what constitutes a heavy metal. It is generally understood that heavy metals are environmentally hazardous substances whose deposition in soils and uptake by vegetation affect soil fertility, plant development and productivity. Some commonly accepted ones are Pb, Cd, Cu, Zn, As, Mn and Cr. They share a common trait of being harmful to humans and the environment. For instance, lead (Pb) can cause blood poison. It negatively influences crop growth, yield and quality. Although copper (Cu) is vital for the healthy development of plants, it is harmful to crop growth and becomes a pollutant if accumulated to an excessive level in the soil. Cadmium (Cd) is one of the most phytotoxic heavy metals easily absorbed by vegetables owing to its lipid solubility. At a level of >0.2 mg kg^{-1} in leafy vegetables, it can impose grave threat to human health (Gu et al., 2015). Besides, it also inhibits plant growth and photosynthesis of pigments (Yang and Li, 2011). Thus, it is significant to closely monitor the content of heavy metals in soils, especially in agricultural areas.

Soil contamination by heavy metals can be studied using several methods. The conventional method of field sampling followed by chemical analysis is costly and inefficient (Wu et al., 2005a). Besides, it is also time-consuming and expensive. In comparison, remote sensing-based reflectance spectroscopy is rapid and inexpensive. It functions by remotely capturing electromagnetic radiation reflected from the target. So far hyperspectral sensing has found wide applications, such as in detecting petroleum hydrocarbons (Scafutto et al., 2017), and landmine detection (Makki et al., 2017), as well as detecting heavy metals in soil and vegetation (Liu et al., 2011a). However, the capability of hyperspectral sensing in monitoring heavy-metal contamination in soils competently has not been assessed comprehensively. It particular, whether remote sensing can serve as a viable alternative in large-scale identification of crops under threat of heavy-metal contamination remains unexplored.

The purpose of this paper is to provide a comprehensive review of the literature on remote detection of trace metals in soils and plants. Its objectives are fourfold: (1) to systematically compare different analytical methods that have been used to establish the empirical relationship between heave metal content and its spectral response; (2) to compare different prediction models and the explanatory variables in them to assess their universality; (3) to critically evaluate the utility of different types of sensing and sensing systems in heavy metal detection; and (4) to assess the accuracy of spatial detection achievable and analyze the factors that affect the success of hyperspectral sensing of heavy metals in soils and plants.

2. Field spectral sensing

2.1. Spectral response of typical metals

The spectral behavior of heavy metals in soils or plants is commonly measured using a hyperspectral ASD FieldSpec3 meter over the full visible-mid-infrared (MIR) spectrum (350–2500 nm) at 1 nm resolution (Kooistra et al. 2004; Pandit et al., 2010; Tan et al., 2014; Xia, 2014; Mohamed et al., 2016). This measurement can be undertaken *in situ* or indoors. If measured *in situ*, there is minimal disturbance to the target, but the measured reflectance may be subject to the influence of a variety of factors, such as the ambient environment and solar radiation. This can be avoided by taking the sample to a laboratory where the spectral reflectance is measured in a controlled environment. Prior to any measurement, the collected soil or vegetation samples have to be ground to fine powders to avoid the effect of granulate samples (Kokaly and Clark, 1999). The measurement is frequently repeated a number of times, and the average is used as the final result. Such measured spectral reflectance forms the basis of hyperspectral sensing of heavy metals as close correlation between soil spectral reflectance and heavy metal concentration has been reported by Siebielec et al. (2004), Bray et al. (2009), and Choe et al. (2009). The high degree of correlation between reflectance features and stress indicators highlights the potential of using remote sensing to assess the type and degree of pollution damage.

Since multiple metals are likely to be co-present in the soil, the exact spectral response of a given metal is usually isolated through simulation in which a plant is exposed to varying levels of a metal in the soil (Dunagan et al., 2007). For instance, potted plants of barley (*Hordeum volgare*) were subject to Zn and Cd treatment for up to 5–6 weeks during which diffuse reflectance spectra were measured daily of the plant canopies (Sridhar et al., 2007a). After *Salicornia virginica* was treated with two metals, its reflectance was found to be sensitive to early stress levels for cadmium (Rosso et al., 2005). A series of pot experiments were performed to determine the effects of soil Cd on *Brassica juncea* chlorophyll content (Yang and Li, 2011). After potted Chinese brake fern (*Pteris vitatta*) was exposed to As and Cr treatments for 22 days, foliar Hg concentrations were correlated positively with soil Hg concentration, even though the correlation varied with the growing season (Sridhar et al., 2007b).