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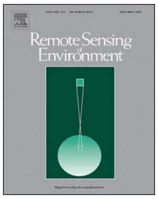

Sensitivity of clay content prediction to spectral configuration of VNIR/SWIR imaging data, from multispectral to hyperspectral scenarios

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ABSTRACT

The use of digital soil mapping, with the help of spectroscopic data, provides a non-destructive and cost-efficient alternative to soil property laboratory measurements. Visible, near-infrared and short wave infrared (VNIR/SWIR, 400–2500 nm) hyperspectral imaging is one of the most promising tools for topsoil property mapping. The aim of this study was to test the sensitivity of soil property prediction results to coarsening image spectral resolution. This may offer an analysis of the potential of forthcoming hyperspectral satellite sensors, e.g., HYPerspectral X IMagery (HYPXIM) or Environmental Mapping and Analysis Program (EnMAP), and existing multispectral sensors, e.g., SENTINEL-2 Multispectral Sensor Instrument (MSI) or LANDSAT-8 Operational Land Imager (OLI), for soil properties mapping. This study used VNIR/SWIR hyperspectral airborne data acquired by the AISA-DUAL sensor (initial spectral and spatial resolutions of approximately 5 nm and 5 m, respectively) over a 300 km^2 Mediterranean rural region. Ten spectral configurations were built and divided in the following two groups: i) six spectral configurations corresponding to simulated sensors with regular spectral resolution from 5 nm to 200 nm (i.e., the Full Width at Half Maximum (FWHM) remains constant throughout the considered spectral domain; this includes the simulation of the forthcoming HYPXIM and EnMAP hyperspectral satellites) and ii) four spectral configurations corresponding to existing multispectral sensors with irregular spectral resolution (i.e., the FWHM differs from spectral sampling interval; Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), SENTINEL-2 MSI, LANDSAT-7 Enhanced Thematic Mapper (ETM+) and LANDSAT-8 OLI). The soil property studied in this paper is the clay content, defined as the percentage of granulometric fraction finer than 2 μm by weight of the soil, which will be estimated using the partial least squares regression method. Our results showed that i) spectral configurations with regular spectral resolutions from 5 to 100 nm provided similar and good clay content prediction performances ($R^2_{val} > 0.7$ and $RPIQ > 3$) and allowed clay mapping with correct short-scale variations, ii) the spectral configuration with a regular spectral resolution of 200 nm provided unsatisfactory clay content prediction performance ($R^2_{val} \simeq 0.01$ and $RPIQ \simeq 1.65$) and iii) the ASTER sensor was the only existing multispectral sensor that provided both correct performance of clay content estimation ($R^2_{val} \simeq 0.8$ and $RPIQ \simeq 3.72$) and correct clay mapping. Therefore, clay mapping by the ASTER multispectral data should be pursued while awaiting the launch of forthcoming hyperspectral satellite sensors (e.g., HYPXIM and EnMAP), which will be good candidates for future large clay mapping campaigns over bare soils.

1. Introduction

Soil provides major services such as provisions of food, fiber, carbon sequestration, water purification and storage, soil contaminant reduction, climate regulation, nutrient cycling, biological habitats and gene pools. However, demographic pressure and climate change impact these key environmental functions which must be monitored, explored and studied. Many models and indicators that represent these functions are now available (Sanchez et al., 2009). To be fully operational for assisting decisions at local, national and global levels, precise spatially

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referenced soil information is required as input in these models and indicators. To address this situation, hyperspectral visible, near-infrared and short-wave infrared (VNIR/SWIR, 400–2500 nm, with > 100 spectral bands) imagery can be considered as an adequate technology for accurate mapping and monitoring of some key soil surface properties (e.g., Ben-Dor et al., 2002; Selige et al., 2006; Stevens et al., 2010; Gomez et al., 2012a). Accurate local estimates were obtained by hyperspectral VNIR/SWIR imagery over bare soil surfaces for soil properties: i) related to a chemical component that impacts soil surface reflectance through absorption bands (e.g., OH^- ions for clay) or ii) highly correlated with the latter (e.g., Cation Exchange Capacity when it is correlated with, for example, clay content) (Ben-Dor et al., 2002). Moreover, recent studies showed that to be predictable, the soil properties have also to have a quite high amount of variability over the study area (Gomez et al., 2012a, 2012b). Nevertheless hyperspectral VNIR/SWIR imagery cannot be extended to large surface mapping or to temporal monitoring because of the expensive cost and the low availability of hyperspectral VNIR/SWIR imaging data.

Only one hyperspectral VNIR/SWIR satellite sensor exists, which is the HYPERION sensor with a spatial resolution of 30 m, a spectral resolution of 10 nm and a swath of 7.5 km (Folkman et al., 2001). Other existing hyperspectral VNIR/SWIR imaging sensors are airborne sensors, such as the HyMap, AISA-DUAL, Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and HySpex sensors, with spectral resolutions between 5 and 10 nm, spatial resolutions of approximately 2 to 5 m (depending on the flight altitude) and flight prints generally inferior of 400 m^2 (depending on the study case). And at least five hyperspectral VNIR/SWIR satellite sensors are planned to be launched next few years (Table 1).

In addition to the hyperspectral imaging sensors, two others categories of VNIR/SWIR imaging sensors exist: multispectral (< 10 bands) and superspectral (10 < bands < 100). Several VNIR/SWIR multispectral satellite sensors are available, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Abrams and Hook, 2003), LANDSAT-7 Enhanced Thematic Mapper (ETM +) and LANDSAT-8 Operational Land Imager (OLI) sensors, which were launched in 1999 and 2013, respectively (Masek et al., 2001; Roy et al., 2014). The World-View 3 (Kruse and Perry, 2013) and SENTINEL-2 Multispectral sensor Instrument (MSI) (Baillarin et al., 2012) sensors are both VNIR/SWIR superspectral satellite sensors, which were launched in 2014 and 2015, respectively.

In advance of a diversity of emerging and existing VNIR/SWIR satellite sensors and to confront the lack of soil maps around the world, the potential of VNIR/SWIR satellite sensors for soil properties mapping must be studied. The effect of spectral resolutions effects on minerals and plants identification were studied by Swayze et al. (2003), by simulations of four imaging spectrometers (including AVIRIS sensor). Van Der Meer et al. (2014) demonstrated the relevance of using bands ratios based on simulated SENTINEL-2 MSI data for ferric iron, ferrous iron, laterite, gossan, ferrous silicate and ferric oxides mapping. The effect of coarsening spatial resolution (from 5 m to 60 m) on the accuracy of clay content (defined as the percentage of granulometric fraction inferior to 2 µm by weight of the soil, Baize and Jabiol, 1995) prediction models was studied by Gomez et al. (2015). They found that, up to a spatial resolution of 30 m, clay mapping was still possible, but beyond a spatial resolution of 15 m, clay content variations due to short-scale successions of parent materials were not precisely captured. In addition, spatial resolutions of 60 m or coarser were not suitable for clay content mapping over areas characterized by small short-scale clay content variability and small field sizes. The effect of coarsening spectral resolution (from 1 nm to 200 nm) on the accuracy of soil properties prediction models was studied only from laboratory spectral databases. Castaldi et al. (2016) conducted a study using several laboratory spectral databases to compare the performances of soil texture and soil organic content estimation from present (EO-1 ALI and Hyperion, LANDSAT-8 OLI, SENTINEL-2 MSI) and forthcoming (EnMAP, PRISMA and HyspIRI) multi and hyperspectral sensors. Adeline et al. (2017) used a laboratory spectral database to compare estimation performances of four soil properties (with different spectral absorption features due to their various physico-chemical interactions with soil substrates), clay content, free iron oxides, calcium carbonate and pH, from seven spectral configurations (number of spectral bands decreasing from 328 to 10 and coarsening spectral resolution from 3 nm to 200 nm). Concerning the clay content, Castaldi et al. (2016) and Adeline et al. (2017) demonstrated that coarsening spectral resolution on lab spectra induces a small decrease in prediction model performance, as this soil property has large and pronounced spectral features. Clay content is often used as a tested soil property since its estimation by VNIR/SWIR spectroscopy is driven by both:

- An absorption band centered around 2200 nm, as clay granulometric fractions is correlated to clay minerals which induce an absorption band centered around 2200 nm due to the combination of vibrations associated with the OH bond and the OH—Al—OH bonds (e.g., Hunt et al., 1971; Chabrillat et al., 2002; Kariuki et al., 2004),
- And the general shape of the spectrum as the particle size influences both spectral intensity and absorption bands depth (Baumgardner et al., 1985; Ben-Dor and Banin, 1995). At fine particle sizes, surface scattering dominates so albedo is high and the expression of absorption features worsens as path length (transmission through particles) in minerals is short. And the more the grain size increases, the more the surface to volume ratio decreases, so albedo decreases and absorption begins to dominate as path length increases in minerals. Thus, spectrum with high content of clay fraction will tend to have higher albedo than spectrum of sandy or loamy soil. Finally, the particle size usually doesn't affect the absorption bands position (Ben-Dor and Banin, 1995).

The present study complements both previous works (Adeline et al., 2017 and Castaldi et al., 2016) by assessing the effect of spectral resolution on clay topsoil property estimation. We simulated both artificial sensors (characterized by regular spectral resolutions) and existing multispectral sensors (characterized by irregular spectral resolutions). All these sensor simulations were based on real airborne hyperspectral VNIR/SWIR data acquired over landscapes at a 5-m spatial resolution (AISA-DUAL hyperspectral sensor). The simulation of sensors allowed us to assess the influence of the spectral resolution on estimated soil property, independently to others specifications (e.g. spatial resolutions, acquisition dates, signal to noise ratio).

Table 1
Characteristics of planned hyperspectral VNIR/SWIR satellite sensors.

Sensor name	Sensor acronym	Nationality	Spatial resolution	Spectral resolution	References
PRecursore IperSpettrale della Missione Applicativa	PRISMA	Italian	30 m	10 nm	Lopinto and Ananasso, 2013
Environmental Mapping and Analysis Program	EnMAP	German	30 m	from 6.5 nm to 10 nm	Guanter et al., 2015 http://www.enmap.org/
HYPerspectral X Imagery	HYPXIM	French	8 m	from 10 nm to 14 nm	Lefèvre-Fonollosa et al., 2016
Spaceborne Hyperspectral Applicative Land and Ocean Mission	SHALOM	Italy-Israel	10 m	10 nm	Ben-Dor et al., 2014
Hyperspectral Infrared Imager	HyspIRI	American	60 m	10 nm	Lee et al., 2015