Remote Sensing of Environment 179 (2016) 54–65

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Evaluation of the potential of the current and forthcoming multispectral and hyperspectral imagers to estimate soil texture and organic carbon

Fabio Castaldi [a],*, Angelo Palombo [b], Federico Santini [b], Simone Pascucci [b], Stefano Pignatti [b], Raffaele Casa [a]

[a] *Department of Agricultural and Forestry scieNcEs (DAFNE), Università degli Studi della Tuscia, Via San Camillo de Lellis, 01100 Viterbo, Italy*

[b] *Consiglio Nazionale delle Ricerche-Institute of Methodologies for Environmental Analysis (C.N.R.-IMAA), Via del Fosso del Cavaliere, 100, 00133 Roma, Italy*

ARTICLE INFO

Article history:
Received 2 August 2015
Received in revised form 2 March 2016
Accepted 23 March 2016
Available online 3 April 2016

Keywords:
Imaging spectroscopy
Sand
Clay
Spectral library
SNR
PLSR
PRISMA
EnMAP
HyspIRI

ABSTRACT

In this study the capabilities of seven multispectral and hyperspectral satellite imagers to estimate soil variables (clay, sand, silt and organic carbon content) were investigated using data from soil spectral libraries. Four current (EO-1 ALI and Hyperion, Landsat 8 OLI, Sentinel-2 MSI) and three forthcoming (EnMAP, PRISMA and HyspIRI) satellite imagers were compared. To this aim, two soil spectra datasets that simulated each imager were obtained: (*i*) resampled spectra according to the specific spectral response and resolution of each satellite imager and (*ii*) resampled spectra with declared or actual noise (radiometric and atmospheric) added. Compared with those using full spectral resolution data, the accuracy of Partial Least Square Regression (PLSR) predictive models generally decreased when using resampled spectra. In the absence of noise, the performances of hyperspectral imagers, in terms of Ratio of Performance to Interquartile Range (RPIQ), were generally significantly better than those of multispectral imagers. For instance the best RPIQ for sand estimation was obtained using EnMAP simulated data (2.56), whereas the outcomes gained using multispectral imagers varied from 1.56 and 2.28. The addition of noise to the simulated spectra brought about a decrease of statistical accuracy in all estimation models, especially for Hyperion data. Although the addition of noise reduced the performance differences between multispectral and hyperspectral imagers, the forthcoming hyperspectral imagers nonetheless provided the best RPIQ values for clay (2.16–2.33), sand (2.10–2.17), silt (2.77–2.85) and organic carbon (2.48–2.51) estimation. To better understand the impact of spectral resolution and signal to noise ratio (SNR) on the estimation of soil variables, PLSR models were applied to resampled and simulated spectra, iteratively increasing the bandwidth to: 10, 20, 40, 80 and 160 nm. Results showed that, for a bandwidth of 40 nm, i.e., a spectral resolution lower than that of current and forthcoming imagers, the estimation accuracy was very similar to that obtained with a higher spectral resolution.

Forthcoming hyperspectral imagers will therefore improve the accuracy of soil variables estimation from bare soil imagery with respect to the results achievable by current hyperspectral and multispectral imagers, however this improvement is still too limited, to allow an accurate quantitative estimation of soil texture and SOC. This work provides useful indications about what could be expected, for the estimation of the most important soil variables, from the next generation of hyperspectral satellite imagers.

1. Introduction

Understanding variability of soil properties between and within agricultural fields allows for more efficient use of resources, improving agronomic and environmental management. The qualitative information included in existing soil maps is often insufficient for site-specific management strategies concerning water, fertilizers, herbicides or harvest. For these purposes, the quantitative estimation of soil properties (e.g., soil texture, organic carbon, nitrogen, and soil moisture) over the field is necessary. With the exception of a few regions in highly developed agricultural environments, this kind of information is rarely available to land managers.

Remote sensing data can be used to obtain, in a very cost effective way, qualitative and quantitative information about soil variables and soil classification (Mulder, de Bruin, Schaepman, & Mayr, 2011). In cultivated soils, due to repeated tillage operations, soil properties are usually quite uniform over the tilled layer; therefore they can be estimated from the bare soil surface reflectance (Casa, Castaldi, Pascucci, Palombo, & Pignatti, 2013).

Quantitative estimation of soil variables using bare soil imagery acquired from multispectral remote imagers is, however, hampered by inadequate spectral resolution, particularly by the absence of narrow bands in the short wave infra-red (SWIR) region (1100–2400 nm) (i.e., the spectral region more affected by the soil chromophores). For

---

* Corresponding author.
E-mail address: castaldi@unitus.it (F. Castaldi).

http://dx.doi.org/10.1016/j.rse.2016.03.025

these reasons, multispectral satellite data are mainly used for qualitative assessments, such as the classification of areas with different soil textures (e.g., Demattê, Fiorio, & Ben-Dor, 2009; Odeh & McBratney, 2000; Zhai, Thomasson, Boggess, & Sui, 2006). Recent studies obtained a sufficient degree of accuracy in the quantitative estimation of silt (Wu et al., 2015) or clay (Castaldi et al., 2014) using, respectively, BJ-1 and Advanced Land Imager (ALI) satellite imagers. It should be noted that both the multispectral ALI imager on board the NASA EO-1 satellite and the Operational Land Imager (OLI) imager on board the Landsat 8 satellite, have bands in the SWIR region, which can be exploited for soil properties estimation. Sentinel-2, which was successfully launched in June 2015, has a Multispectral Imager (MSI) with a band in the SWIR region, between 2100 and 2280 nm and centred at 2190 nm, with a Ground Sampling Distance (GSD) of 20 m.

Hyperspectral imagers, that measure spectral radiance for hundreds of narrow bands are more attractive than multispectral imagers for soil spectroscopy purposes. Furthermore, over the last decade, analysis of data obtained by optical remote sensing techniques derived from soil spectroscopy and hyperspectral imagery has proven to be an effective way to characterize and monitor surface soil variables, that even allow soil erosion processes to be detected (Gomez, Oltra-Carrió, Bacha, Lagacherie, & Briottet, 2015; Stevens, Nocita, Tóth, Montanarella, & van Wesemael, 2013; Ben-Dor et al., 2009; Lagacherie, Baret, Feret, Netto, & Robbez-Masson, 2008; Gomez, Viscarra Rossel, & McBratney, 2008). The higher spectral resolution provided by hyperspectral sensors could, in principle, allow even more accurate quantitative estimates at the field scale, compared with those obtainable from the existing multispectral imagers (Mulder et al., 2011).

Only two hyperspectral satellite imagers with a sufficient spatial resolution (i.e., GSD ≤ 30 m) are currently available for soil applications: Hyperion on board of the NASA EO-1 platform and Compact High Resolution Imaging Spectrometer (CHRIS) on the European Space Agency's PROBA platform. Both these sensors have considerable limitations in quantitative soil estimation applications. Hyperion's data are hampered by the very low signal to noise ratio (SNR) in the SWIR region, in particular around 2200 nm, where the spectral features of clay minerals are located (Castaldi et al., 2014). The difficulties in estimating soil variables from CHRIS-PROBA are due to its restricted spectral range (415–1050 nm) that lacks bands in the SWIR region (Casa, Castaldi, Pascucci, Basso, & Pignatti, 2013). For these reasons, the use of satellite hyperspectral data in quantitative soil estimation is still challenging and consequently the number of published studies in which this type of data are used is still small (Casa, Castaldi, Pascucci, Basso et al., 2013; Casa, Castaldi, Pascucci, Palombo et al., 2013; Castaldi et al., 2014; Gomez et al., 2008; Zhang, Li, & Zheng, 2013).

In the near future at least four satellites equipped with hyperspectral imagers are due to be launched: the Japanese Hyperspectral Imager Suite (HISUI) in 2017 (Tanii, Iwasaki, Kawashima, & Inada, 2012); the Italian PRecursore IperSpettrale della Missione Applicativa (PRISMA) in 2017 (Pignatti et al., 2012); the German Environmental Mapping and Analysis Program (EnMap) in 2018 (Richter, Hank, Atzberger, Locherer, & Mauser, 2012); the China Commercial Remote-sensing Satellite System (CCRSS) after 2018; and the U.S. NASA Hyperspectral Infrared Imager (HyspIRI) in 2021 (Houborg, Anderson, Gao, Schull, & Cammalleri, 2012). The Spaceborne Hyperspectral Applicative Land and Ocean Mission (SHALOM) — a joint mission by the Israel Space Agency (ISA) and the Italian Space Agency (ASI) — will also develop a hyperspectral imager with 241 bands between 400 and 2500 nm and a spectral resolution of about 10 nm (Ben-Dor, Kafri, & Varacalli, 2013). A new hyperspectral imager, HYPerspectral X Imagery (HYPXIM) is also under study by the French space agency (CNES) (Michel, Gamet, & Lefevre-Fonollosa, 2011). Forthcoming hyperspectral imagers will have numerous narrow bands in the SWIR spectral region, which will presumably permit accurate estimation of soil variables; however, the soil properties estimation accuracy of these imagers will depend on their SNR, particularly around 2200 nm. Hyperspectral imagers generally have a lower SNR than multispectral ones as a result of the reduced energy collected by the sensor in narrow spectral bands. This effect, coupled with the low solar irradiance in the SWIR region, produces a consistent decrease of the SNR. For example, Castaldi et al. (2014) compared the soil estimation capabilities of two sensors mounted on EO-1 satellite using both Hyperion and ALI data. The authors did not observe any apparent advantages when using hyperspectral (Hyperion) instead of multispectral (ALI) data. This was explained by the low SNR of Hyperion at the wavelengths of characteristic spectral features of clay minerals.

This study aims to evaluate the performances of current and forthcoming multispectral and hyperspectral imagers for the quantitative retrieval of soil texture and Soil Organic Carbon (SOC). To this end we compare the estimation accuracy for soil texture (clay, sand and silt) and SOC using spectra acquired under laboratory conditions, which were resampled according to spectral and noise characteristics of four current (ALI, Landsat 8, Sentinel-2 and Hyperion) and three forthcoming (EnMAP, PRISMA, HyspIRI) satellite imagers. To our knowledge, no previous reports have specifically compared the capability of these imagers for soil texture and SOC estimation.

2. Materials and methods

2.1. Soil spectral libraries

2.1.1. PONMAC library

A soil spectral library consisting of 166 samples was assembled by pooling together data from soil samplings obtained from two cropland areas in Central and Southern Italy. Samplings were carried out in Pontecagnano (PON; Southern Italy, near to Salerno) and Maccarese (MAC; Central Italy, near to Rome) and a pooled dataset obtained from the union of PON (Pascucci et al., 2014) and MAC (Casa, Castaldi, Pascucci, Palombo et al., 2013), hereafter referred to as PONMAC. The soils of the MAC area are classified as Cutanic Luvisol (FAO-ISRIC-ISSS, 1998), with soil parent materials of flat inshore deposits (Pleistocene), while the soils of PON area originated from travertine sediments characterized by sandy gravel layers with tuffaceous intercalation in the upper parts (Pleistocene–Holocene). In both areas, soil sampling was carried out using a gouge auger at 0–10 cm depth in Pontecagnano and at 0–30 cm depth in Maccarese. Soil samples were air dried and passed through a 2 mm sieve. For each sample we measured the percentage of clay, sand and silt contents using the pipette method according to the United States Department of Agriculture (USDA) system (Soil Survey Staff, 2014). Soil Organic Content (%) was obtained using the Walkley-Black method for PON data, and an elemental analyzer (Flash EA1112, Thermo Electron Corporation, U.S.A.), according to the technique of dry combustion analysis (ISO 10694, 1995), for MAC data. Although SOC measurements were carried out using different methods for MAC and PON dataset, the results obtained from Walkley-Black and dry combustion analysis were considered to be comparable within the range of SOC values of the PONMAC dataset (Chen et al., 2015).

Soil textures of PONMAC samples are mainly composed of sandy clay loam, clay loam and clay. These textural classes are among the most frequent in the croplands of Italy (Costantini et al., 2012). The ranges of the relative contents (%) of clay, sand and silt in the PONMAC dataset are quite wide (Table 1). The SOC content range is between 0.5 and 2.32%, with a mean value of 1.25% (Table 1).

Soil samples were placed in Petri dishes and their spectral signatures were measured in a dark lab in the visible-near infrared (VNIR) to SWIR optical domain (350–2500 nm, spectral sampling of 1 nm) using an Analytical Spectral Devices (ASD) Field Spec Fr Pro spectroradiometer (ASD Inc., Boulder, CO, USA; available at: http://www.asdi.com) equipped with a contact probe containing a 7 W quartz-halogen lamp. Reflectance values from 350 to 399 nm and from 2401 and 2500 nm were removed prior to any processing because these spectral ranges are affected by noise.