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Field scale mapping of soil carbon stock with limited sampling by the use of proximal sensors

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Abstract

High-precision maps of soil features, namely texture, soil organic carbon, gravels, allow monitoring the effects of specific agricultural managements on carbon stock spatial variability. At a field-scale the assessing of soil spatial variability can be improved by using proximal sensors, which permit a quick and cheap recording of data with a high spatial density.

Aim of the present work was to test the combined use of two proximal sensors, namely visible-near infrared (Vis-NIR) spectrometer and passive γ-ray spectrometer, to obtain high detailed maps of soil carbon stock at a depth of 0-30 cm (CS_{30}), using a limited number of sampling sites per field (around 1 per hectare). CS_{30} maps were interpolated within surveyed fields using Geographically Weighted Multiple Regression (GWMR). The accuracy of CS_{30} predicted maps allows monitoring of the effects of agricultural management and soil erosion on the soil carbon pool and its spatial variability.

Keywords: mapping, spectroscopy, geostatistics, erosion, management, Sicily, Italy.

Introduction, scope and main objectives

Assessment of soil spatial variability at high-detail can be very useful to comprehend the effects of management and/or erosion on soil services in all the parts of the field or basin. However, mapping soil features at high detail usually has high cost, is time-consuming for high number of sampling, and the results are often questionable. The use of proximal sensors allows a quick and cheap recording of data with a very high spatial density. Although soil features predicted by proximal soil sensing may be less accurate than conventional methods, the collection of larger amounts of spatial data using quicker, cheaper, and simpler techniques makes their use very efficient (Viscarra Rossel et al., 2009).

The aim of the present work was to test the combined use of two proximal sensors, namely visible-near infrared (Vis-NIR) and passive γ-ray spectrometers, to obtain high detailed maps of soil C stocks at a depth of 0 to 30 cm (CS_{30}) using a limited number of sampling sites per field, which were around 1 sample per hectare.

Over the past 30 years, Vis-NIR diffuse reflectance spectroscopy (Vis-NIR DRS) has proven to be a quick, cost-effective and non destructive method to predict several soil features, in particular soil organic carbon (SOC), water content, texture, and carbonates (Viscarra Rossel et al., 2009; Stenberg et al., 2010). The accuracy of SOC determination by Vis-NIR DRS was slightly lower than that obtained by Walkley-Black and TOC analyser, but the unitary cost was €0.96 with Vis-NIR, versus €2.56 with Walkley-Black and €15.15 with TOC analyser (O'Rourke and Holden, 2011). Vis-NIR DRS could be used both in laboratory and in field, the latter using rugged spectrometers and equation to correct spectra for soil moisture.

The use of passive γ-ray spectrometry for mapping radionuclide concentrations in soils and rocks has been used since the 1960-70 for mineral exploration and geological mapping, but in the last decade it has been also used for soil mapping and agricultural purposes (Van der Klooster et al., 2011; Dierke and Werban, 2013; Priori et al. 2014). Such methodology can provide high-precision maps of topsoil spatial variability (0-30 cm), in particular related to mineralogy, texture and stoniness.

Methodology

Study area

The study area was situated in the western part of Sicily (southern Italy) in the "European Soil region 62.2", described as hills of Sicily on clayey flysch, limestone, sandstone, and coastal plains with Mediterranean subtropical climate (Costantini et al, 2013). The fields surveyed during this work had a surface ranging between 2 and 6 ha, and they were dislocated into nine areas, cultivated with extensive row-croplands. The parent materials of the experimental fields included clays, silty-clays and marls clayey-silty deposits of marine origin (Miocene-Pliocene), as well as clayey-calcareous flysches and calcarenites of Cretaceous-Paleogene. The soils of the areas generally showed high clay content and carbonates, and they were classified as *Vertic Calcisols, Calcaric Vertisols, Calcaric Cambisols, Fluvic Cambisols* and *Calcaric Regosols*.

The proximal soil survey by γ-radiometrics and the soil sampling were carried out in the middle of April 2013 and 2014, in very similar climate and soil moisture conditions (about 15-20 $dag \cdot kg^{-1}$). The sensor used for such survey was "The Mole", a commercial γ-ray spectrometer with a CsI-crystal of 70x150 mm (Van Egmond et al., 2010). The sensor was carried within the fields in a dedicated backpack and it was connected to a GPS and a rugged laptop, which recorded coordinates and γ-ray spectra (about one spectra/second). The total count of γ-ray (TC) and the nuclide concentrations (^{40}K, ^{238}U, ^{232}Th) were interpolated by ordinary kriging to obtain grid maps at 1 m spacing.

Simultaneously with the y-radiometric surveying, 208 soil samples (0-30 cm deep) were collected using a regular grid sampling pattern, with a frequency of 8 samples per hectare.

The samples, previously dried and 2-mm sieved, were scanned by Visible-Near Infrared Diffuse Reflectance spectroscopy (Vis-NIR DRS), using a Fieldspec 3 Hi-Res® (ASD Inc., Boulder, CO), which has bands ranging between 350 and 2500 nm. White referencing was carried out every 10 soil samples, using a Spectralon® panel.

The commercial software Unscrambler X (CAMO software AS., Oslo, Norway) was used for spectra pre-processing (Multiplicative Scatter Correction, first derivation, head and tail spectra removing) and modelling. The models used to predict soil features by Vis-NIR DRS need careful selection of the calibration dataset, which should be large (several hundreds or thousands of samples) and representative of the prediction dataset (Stenberg et al., 2010).

The selection of the soil samples, analysed by conventional laboratory analysis, and then used for calibration set, was carried out after grouping through cluster analysis. The most representative sample of each cluster, which was the sample with the lowest Euclidean distance for that cluster, was selected for calibration. The number of samples that we decided to use for calibration was 1 per hectare, with a minimum of 3 samples per study area.

Therefore, from the total amount of 208 samples, only 32 samples were selected for calibration set. Other 36 samples were selected for validation of PLSR model, and other 36 samples were used to validate the final maps of carbon stock. The three subsets of samples were analysed with laboratory conventional method. Clay and sand content were analysed by pipette method, and SOC was analysed by Walkley-Black method and converted to International Organization for Standardization standard (ISO 14235).

Other 53 soil spectra of our own spectral library, already analysed and belonging to the same Soil Region and parent material, were extracted. Therefore, the complete calibration dataset include 85 soil samples with high pedological and lithological similarity.

Partial Least Square Regression (PLSR), implemented in Unscrambler X, was used to develop calibration models to predict CS_{30} of the fine earth ($CS_{30}f$) from Vis-NIR DRS spectra. The model efficiency was calculated with the external validation set of 36 samples, by coefficient of determination (R^2), root mean square error of the prediction (RMSE), and the residual prediction deviation (RPD).

$CS_{30}f$ values were corrected for the gravel content, according to IPCC LULUCF guidelines (IPCC, 2003).

Afterwards, the interpolation of CS_{30} at each site was carried out through Geographical Weighted Multiple Regression (GWMR), using as covariates the γ-ray maps (total counts and radionuclides concentration).

The final validation of the CS_{30} maps were carried out using the other 36 independent data points analysed by standard laboratory methods.

Results

Total counts (TC) of γ-ray spectroscopy varied between 170 and 520 $Bq \cdot kg^{-1}$ and had a mean standard deviation within each site of about 22 $Bq \cdot kg^{-1}$. Some fields showed higher spatial variability, mainly due to the presence of strongly eroded areas characterized by thin soils, high stoniness, and scarce soil organic matter. ^{40}K radionuclide showed mean values between 27.2 and 41.8 $Bq \cdot kg^{-1}$, which are comparable with the mean values measured in calcareous and clayey parent materials in a previous work (Priori et al., 2014). ^{232}Th and ^{238}U showed low values in all the studied areas.

Calibration set using for $CS_{30}f$ prediction by Vis-NIR DRS showed mean and standard deviation values of 4.92 and 1.31 $kg \cdot m^{-2}$, respectively. PLSR model of $CS_{30}f$ showed its best efficiency using 6 principal components, which explained 86.6% of the total variance. The coefficient R^2 of the model was 0.86 and the RMSE was 0.43 $kg \cdot m^{-2}$. The external validation set of 36 samples showed a coefficient R^2 of 0.77, RMSE of 0.67 $kg \cdot m^{-2}$, and RPD of 2.06 (Fig.1b). Although the RMSE did not point out very high precision, the errors can be considered acceptable, considering the high standard deviation of the $CS_{30}f$.

Relationships between CS_{30} (after correction for gravel content) and γ-ray spectroscopy data provided general low correlations. This result justified the use of a non-stationary regression method, such as geographical weighted regression, calculated in each study area, separately.

The interpolation of CS_{30} (Fig. 1a), carried out within each area through the Geographical Weighted Multiple Regression (GWMR), provided maps with acceptable accuracy (R^2 between 0.76 and 0.93). The validation of the CS_{30} maps with the external set of the 36 samples, showed R^2 of 0.69, RMSE of 0.59 $kg \cdot m^{-2}$ (Fig. 1c), and RPD of 1.93.

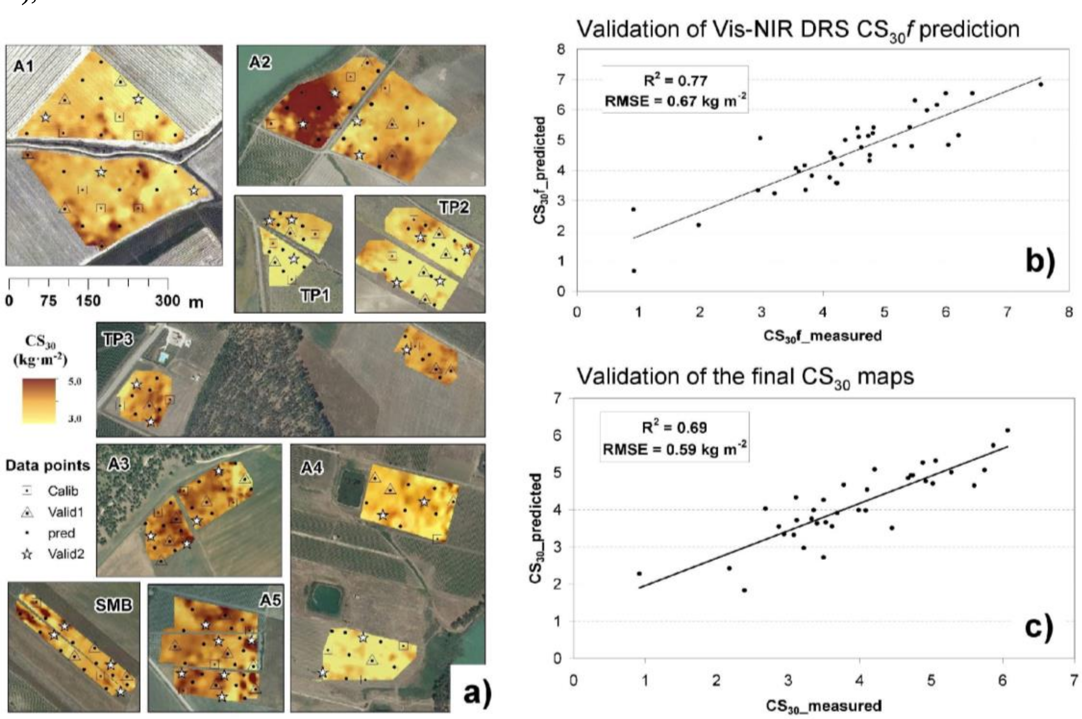

Fig. 1: Predicted maps of carbon stock CS_{30} with calibration and validation sites (a). On the right, the validation results of carbon stock of the fine earth (< 2mm, $CS_{30}f$) predicted by Vis-NIR DRS (b) and the final validation of the maps after geographical weighted multiple regression, using γ-ray maps as covariates (c). The images and the results of this work was already published in Priori et al. 2016.

Discussion

The research work demonstrates that working out a predictive model to estimate directly soil carbon stock by Vis-NIR DRS is possible, and the obtained accuracy of the model is good, even if the number of samples for calibration was limited (n= 32). A limited number of samples to calibrate a reliable PLSR model was possible since other similar soils were recorded in our own spectral library. Vis-NIR DRS allowed to save the laboratory analysis cost of 176 samples. According to the cost estimation of O'Rourke and Holden (2011), the total savings to calculate $CS_{30}f$ were about 9.80 € per sample**.**

The general correlation between γ-ray data and soil features showed some significant, but low, relationships for SOC, clay, sand, gravel, and CS_{30}. This means that some correlations between γ -ray spectroscopy data and soil features exist, but the relationships are strongly site-specific. For this reason it was impossible to apply a general regression model to predict maps of CS_{30} using γ-ray data covariates, and it was impossible to calculate covariogram because of scarcity of datapoints per field.

The use of Geographical Weighted Multiple Regression (GWMR) exceeded these problems, by the application of spatial weights to the regression.

The validation carried out within each field showed higher accuracy in two fields (A1 and TP1), whereas other two fields showed the lowest accuracy (A2 and SMB). This was mainly due to very few samples that had high error of prediction, due to unknown causes. Actually, radionuclides in the agricultural soils are influenced by several factors not always clear, including water chemistry, relocation of soil because of land leveling or erosion, accumulation of fertilizers, and other chemical pollution.

Conclusions

The paper shows an innovative methodology to interpolate soil organic carbon stock at high-detail within arable fields, coupling two methodologies of soil proximal sensing, namely Vis-NIR and γ-ray spectroscopy. The methodology described in this work makes use of a limited number of samples per field, around 1 per hectare, saving time and money for laboratory analysis.

The accuracy of CS_{30} maps allows the use of such maps for several purposes, like comparing the effects of different soil management strategies in agriculture and monitoring the effects of soil erosion on soil carbon pool.

The methodology proposed in this paper constitutes an innovation, but the use of γ-ray spectroscopy as covariate to interpolate carbon stock needs additional studies.

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