



Satellite data and soil magnetic susceptibility measurements for heavy metals monitoring: findings from Agri Valley (Southern Italy)

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Abstract

Heavy metals pollution is a widespread problem in urbanized and industrial areas and there is a need of optimized and effective strategies for identifying and monitoring polluted areas. This study proposes an improved methodology based on Landsat satellite data and magnetic susceptibility measurements carried out in situ and in laboratory. Findings suggest that expeditious field surveys of soil magnetic susceptibility within stressed vegetated areas are a reliable indicator of soil contamination. Moreover, this procedure could provide a method for assessing heavy metals impacts and could be used to examine the effectiveness of emission control strategies.

Keywords Soil pollution · Heavy metals · Magnetic susceptibility · NDVI · Landsat data

Introduction

Heavy metals contamination of soils is very diffuse in the surroundings of urbanized and industrial areas. It causes serious damages both to the quality of the environment and to human health. It is well assessed that the presence of heavy metals in the particulate matter and/or in soil causes foliar damage (Love et al. 2009), reduces plant growth and decreases yields (Vuletic et al. 2014). Moreover, heavy metals, deposited on vegetation through particulate matter or present in soils in a bioavailable form, end up in the food chain and may endanger human health (Baderna et al. 2015).

Although chemical measurements of heavy metals concentrations in soil are accurate and reliable, they are expensive, time-consuming and not able to take into account the synergic effects of different pollutants. Moreover, their spatial coverage and temporal repetition are generally inadequate for a satisfactory estimation of pollution phenomena over large areas. In order to overcome these limitations, it is

fundamental to promote the development of effective monitoring strategies.

Soil magnetic susceptibility measurements are extensively used as proxy variables for monitoring soil heavy metals of anthropogenic origin (D'Emilio et al. 2007; Zhu et al. 2013; Rachwał et al. 2017). They are used as a proxy for environmental metal contamination in soil so these measurements do not give us the concentration values of a single metal in soil, but they indicate the presence of heavy metals linked to magnetic particles (Fabijańczyk et al. 2016; Golden et al. 2017).

One of the advantages of the magnetic approach, often supported by chemical measurements, is to identify restricted areas with high pollution levels (D'Emilio et al. 2010).

On the other hand, remote sensing techniques have become an important tool for monitoring the development of environmental issues over large areas (Albergel et al. 2013; Imbrenda et al. 2014). They are useful also to follow the dynamic of the processes involved in pollution phenomena by using vegetation as reliable bioindicator of the general health conditions of the examined areas. In fact, as a pivotal link between atmosphere and soil, vegetation normally responds rather quickly to subtle environmental changes of both natural and anthropic origins, included heavy metals contaminations (Gallagher et al. 2008). Nowadays, there are few studies integrating geophysical surveys and remote sensing techniques aimed to the monitoring of soil pollution

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(D’Emilio et al. 2012; Alexakis et al. 2014). In Alexakis et al. (2014), an integrated approach for monitoring pollution due to olive oil mill wastes is proposed and preliminary results suggest that the procedure is useful for studying and understanding this kind of land pollution. In D’Emilio et al. (2012), an experimental procedure for heavy metals monitoring, based on the integration of remote sensing data and magnetic susceptibility measurements supported by chemical measurements, was proposed. In this work, we use satellite images to estimate levels of vegetation stress (altered photosynthetic activity, see Reusen et al. 2003; Zhou et al. 2017) likely associated with the influence of heavy metals and we are not interested in using them for detecting the amount of heavy metals in soils.

In this paper, a new field survey carried out during the summer 2011, aimed to upgrade this procedure in a more feasible and cost-effective manner, is proposed.

Study area

The monitored area (about 6 km²) is located in Agri Valley (Southern Italy) and is characterized by a quite uniform geology (alluvial soils). It suffers a great anthropogenic pressure due to oil extraction and pre-treatment activities. The main industrial settlement of this area is the oil/gas pre-treatment plant Centro Olio Val d’Agri (COVA). The field survey was carried out during June 2011 along the sampling

grid shown in Fig. 1. It was composed of 21 sampling points located at a distance of about 200 m from each other, chosen on the base of their accessibility and proximity to the pollution sources, following substantially the layout of the previous field survey (D’Emilio et al. 2012).

Materials and methods

Soil magnetic susceptibility both in situ and in laboratory was measured, and a Landsat 5-TM image of the study area, acquired in the same year and season of the field survey, was used to compute the Normalized Difference Vegetation Index (NDVI) which is considered a reliable proxy for plant greenness and photosynthetic activity. Finally, the relationships between soil magnetic susceptibility measurements and NDVI anomalies were analysed.

Magnetic susceptibility measurements

Magnetic susceptibility measurements were performed using a Bartington MS2 meter with two field survey probes MS2D (penetration depth of about 10 cm) and MS2F (effective penetration depth of about 1 cm) and with MS2B laboratory dual frequency sensor. The probes measure volume magnetic susceptibility, expressed as dimensionless value $\times 10^{-5}$ SI, and the accuracy of measurements is 5%. The sampling procedure shown in D’Emilio et al. (2007, 2010) was used.

Fig. 1 Study area: AGEA aerial image with the overlay of the sampling grid. Yellow bullets indicate sampling points, whereas white numbers identify the three classes of the same pedological region (Region 8—Soil of river basins and internal floodplain of the Apennine Mountains—Southern Italy) as reported in <http://www.basilicata.net.it/suoli/provincia8.htm>



Satellite data

A subset of a Landsat 5-TM satellite image acquired on 2 August 2011 (path 188 and row 032 GTCE) with 30 m of spatial resolution was processed and analysed. The selected scene, available at no-cost (<http://glovis.usgs.gov/>), was completely free of clouds in the study area. Radiometric calibration (digital number–radiance–reflectance conversion) for satellite image channels was performed according to the procedure reported in Chander and Markham (2003), Barsi et al. (2007). Then, RED (band 3) and NIR (near infra-red-band 4) reflectances were selected to compute NDVI according to the following formula:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED}) \quad (1)$$

NDVI values range from 0 to 1. High NDVI values are associated with healthy/dense vegetation, and low NDVI values characterize stressed and/or sparse vegetation.

Subsequently, a land cover map at the same sensor spatial resolution (30 m) was elaborated by using a consolidated procedure already tested in the study area (Simoniello et al. 2015) based on an hybrid unsupervised/supervised classification. For the preliminary class labelling (unsupervised step) as well as for the selection of training areas (supervised step), an aerial image acquired in the spring of 2011 by AGEA (Italian Rural Payments Agency) was used. For each defined land cover class, mean values of NDVI were calculated, and then, the NDVI anomalies per pixel (NDVI*) were computed as the departure of the current NDVI values from the mean values of the relative land cover class (D'Emilio et al. 2012; Lanfredi et al. 2015):

$$\text{NDVI}_i^* = \frac{\text{NDVI} - \mu_i(\text{NDVI})}{\sigma_i(\text{NDVI})} \quad (2)$$

where μ and σ are, respectively, the mean value and the standard deviation of NDVI for each defined land cover class.

Data integration and calculations were performed in the QGIS 2.18.2 environment. The geographic information was projected to a common UTM zone 33 under the WGS84 datum.

Results and discussion

The results of magnetic susceptibility field survey, i.e. MS2D (K_D), MS2F (K_F), MS2B high frequency (K_{BH}) and low frequency (K_{BL}) probe data, are analysed by means of univariate statistics, whereas the relationships among magnetic susceptibility measurements and NDVI anomalies are analysed by means of a bivariate statistical procedure.

Figure 2 shows maps of soil magnetic susceptibility values for the different probes.

The maximum value of K_D is found very close to the industrial area of the COVA (Fig. 2), and the higher values are measured in the north-eastern part of the examined area. K_D mean value (m) is 53×10^{-5} SI; median value is 4×10^{-5} SI; percentage variation coefficient (CV%) is 60%; K_D values range from 16×10^{-5} SI to 106×10^{-5} SI. The kurtosis value (k) is 1, and the skewness is positive. We measured many values distributed around the means and few extreme values.

The maximum value of K_F is measured on the right of the COVA very close to the industrial area. The higher K_F values are measured in the upper part of the investigated area. K_F mean value (m) is 62×10^{-5} SI; median value is 60×10^{-5} SI; CV% is 73%; K_F values range from 2×10^{-5} SI to 188×10^{-5} SI. In this case, the skewness is positive, and $k = 2$. These statistical parameters suggest the presence of many values distributed around the mean value and few extreme values.

For both the laboratory sensors, the higher values of magnetic susceptibility are measured in the north-eastern side of the investigated area.

Other statistics for the laboratory sensors are the following:

K_{BH} mean value (m) is 95×10^{-5} SI; CV% is 87%; K_{BH} values range from 21×10^{-5} SI to 355×10^{-5} SI. The skewness is positive suggesting the presence of peaks. The $k = 4$ indicates that there are only few extreme values.

K_{BL} mean value (m) is 142×10^{-5} SI; CV% was 87%; K_{BH} values range from 25×10^{-5} SI to 449×10^{-5} SI. The skewness was positive, and $k = 1$.

NDVI and NDVI anomalies maps of the study area are shown in Fig. 3. In Fig. 3a, it is possible to identify artificial surfaces characterized by the lowest NDVI values within the study area (mainly coinciding with the COVA), bare soil and little vegetated areas with medium–low NDVI values and a quite wide range of natural and anthropogenic covers including arable land, permanent crops, shrublands and forests with a higher vegetation density and medium–high NDVI values. Figure 3b shows the pattern of NDVI anomalies. Positive anomalies are scattered throughout the study area and characterize vegetation patches having biomass/vigour higher than the average value of the respective land cover class, whereas negative NDVI anomalies identify areas with a vegetation vigour/biomass lower than the average class conditions.

In order to study the relationships among magnetic susceptibility values and NDVI anomalies, we assessed statistical significance by computing Pearson correlation coefficients. Results show statistically significant negative correlations between NDVI anomalies and magnetic susceptibility values, in particular, K_D ($N = 21$, $\rho = -0.82$, $p = 1\%$), K_{BH} ($N = 21$, $\rho = -0.73$, $p = 1\%$), K_F ($N = 21$, $\rho = -0.66$, $p = 1\%$). The scatter plots are shown in Fig. 4.

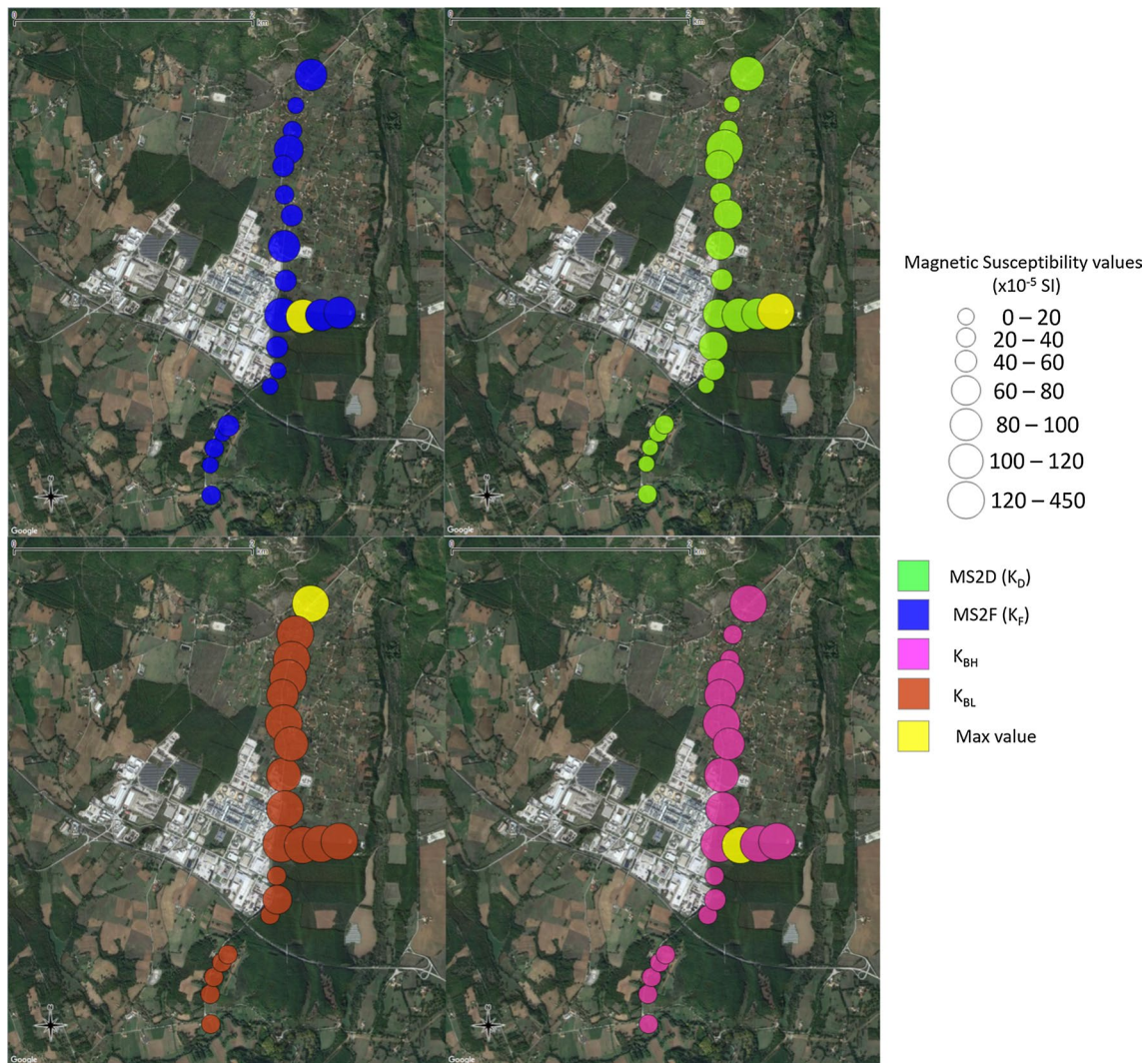


Fig. 2 Soil magnetic susceptibility maps of the investigated area. Soil magnetic susceptibility measured with MS2D is shown with green bullets, MS2F with blue bullets, MS2B high frequency— K_{BH} with

pink bullets—and MS2B low frequency— K_{BL} with red bullets. The yellow bullets indicate the maximum measured value

Correlations indicate principally that high values of magnetic susceptibility were measured in areas showing negative NDVI anomalies, that is, in areas with stressed/degraded vegetation, confirming what had been found in the previous investigation. Moreover, the high magnitude of correlations observed for both in situ and laboratory analyses (MS2D and MS2F) further supports the robustness of the adopted approach, being the laboratory analyses less affected by disturbance effects typical of field conditions.

Furthermore, by separating measurements carried out in anthropic covers (agricultural areas) from those in natural covers (forest, shrublands and sparse vegetated areas) statistically significant correlations are still observed. In

particular, correlations between NDVI anomalies of natural covers and magnetic susceptibility are notable: K_D ($N = 11$, $\rho = -0.85$, $p = 1\%$), K_F ($N = 11$, $\rho = -0.79$, $p = 1\%$) and K_{BH} ($N = 11$, $\rho = -0.78$, $p = 1\%$). For anthropic covers, correlations appear less strong: K_D ($N = 10$, $\rho = -0.80$, $p = 1\%$) and K_{BH} ($N = 10$, $\rho = -0.69$, $p = 5\%$), whereas a not statistically significant correlation is found between NDVI anomalies and K_F . The lower correlation values observed in anthropic covers are probably due to a higher degree of soil mixing linked to the execution of common tillage practices which impede heavy metals deposition and accumulation. Given the normal conditions of temperature and rainfall regime during the year 2011 (information

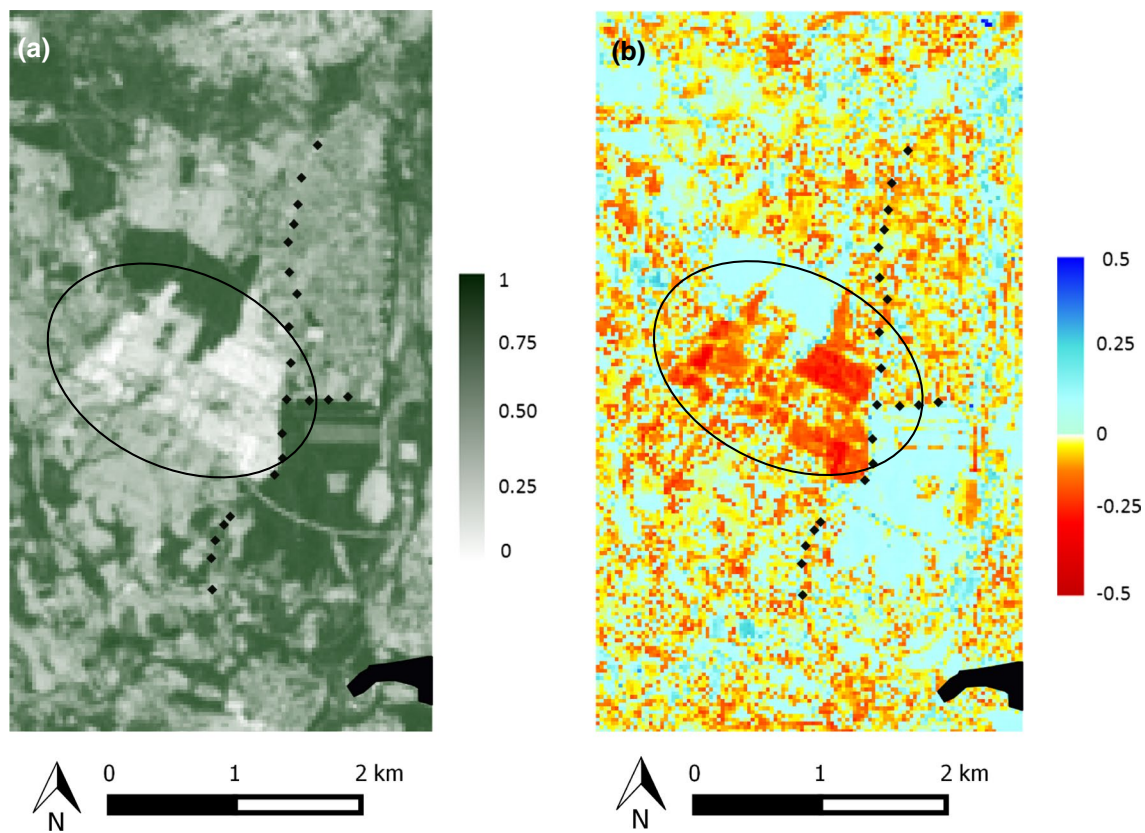


Fig. 3 Normalized Difference Vegetation Index—NDVI (a) and NDVI anomalies (b) maps of the study area. Black diamonds indicate the sampling points; the black ellipse puts in evidence the Centro Olio Val d’Agri (COVA); a black mask is applied on the Pertusillo Lake in the lower right corner. Vegetation with a reduced photosynthetic activity shows low NDVI values, whereas dense and healthy

vegetation shows high NDVI values (a). Negative NDVI anomalies identify areas with a vegetation vigour/biomass lower than the average class conditions; on the contrary, positive anomalies identify areas with a biomass/vigour higher than the average value of the respective land cover class (b)

extracted from the meteorological station of Villa D’Agri, <http://www.alsia.it/sit/mappa3/>) compared with the last 10 years, it can be assumed that vegetation degradation is probably connected with anthropogenic pressure. Hence, it is possible to perform directly expeditious field surveys of magnetic susceptibility measurements for critical urbanized/industrial areas suspected of being contaminated by heavy metals. More detailed investigations based on chemical analyses can be subsequently dedicated to areas showing higher values of magnetic susceptibility.

Conclusions

In this paper, the results of a field survey aimed to update/upgrade a previous procedure for monitoring heavy metals levels in urbanized/industrialized areas, based on in situ and

laboratory soil magnetic susceptibility measurements and freely accessible satellite data, are discussed. The strong correlations found between NDVI anomalies and both in situ and laboratory magnetic susceptibility measurements suggest to use directly expeditious field surveys of magnetic susceptibility (recognized to be significantly correlated with soil heavy metals concentrations) in those areas with insufficient photosynthetic activity (anomalous zones). The time-saving and inexpensive investigation strategy here proposed can be easily exported elsewhere for the assessment and monitoring of potentially contaminated areas located within still vegetated landscapes.

The adopted approach is simple and can be adjusted to local requirements by selecting the most appropriate satellite data at the desired spatial and temporal resolutions (Landsat imagery or the most recent very high-resolution Sentinel 2 dataset).

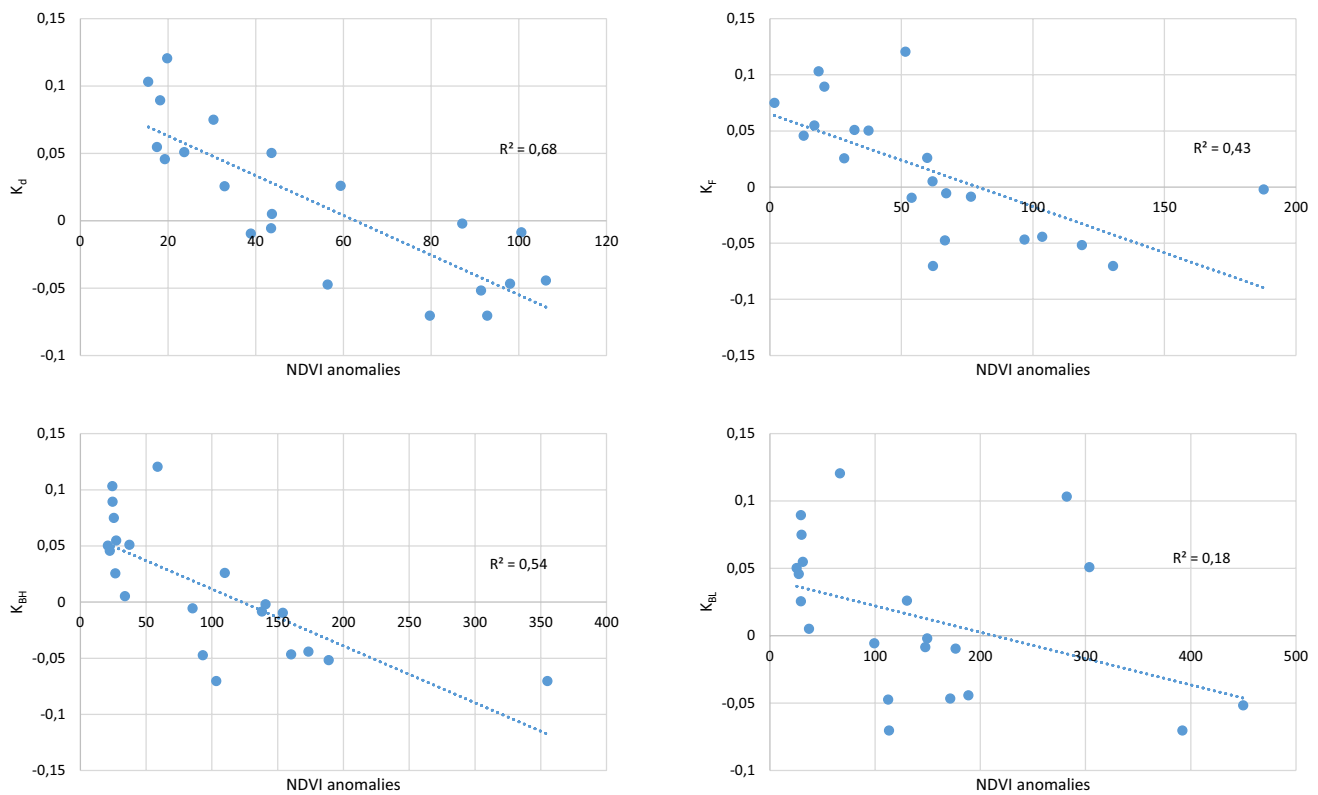


Fig. 4 Scatter plots between magnetic susceptibility measurements and values of NDVI anomalies (NDVI*) estimated on the 2 August 2011 Landsat image

The estimation of heavy metals soil contamination over large areas could provide a reasonable instrument for assessing health impacts and for examining the effectiveness of the emission control strategies.

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