

Mapping Bauxite Mining Residues Using Remote Sensing Techniques [†]

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Abstract: Bauxite residuals from abandoned mining sites are both an environmental challenge and a possible source of secondary raw materials. Processing of multispectral and hyperspectral images with the best available techniques can help to produce multiscale spatial maps of elements inside and around the mining sites. The authors propose a procedure for mapping elements concentration using multiple data sets at different scales and resolutions. A comparison between multispectral Sentinel-2 images and hyperspectral PRISMA processing is performed over some case studies of bauxite residues in the Mediterranean area. Specifically, a case study from Italy is composed regarding artificial canyons created by past artisanal mining activities and by stockpiles of extracted bauxite. Hyperspectral punctual measurements (spectroradiometer surveys) were taken in various zones of the bauxite site, where infield topsoil samples were also taken for X-ray fluorescence chemical analysis. Final concentration maps were estimated by performing geostatistical techniques.

Keywords: bauxite mapping; hyperspectral images; band ratio



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1. Introduction

Bauxite residuals from abandoned mining sites are both an environmental challenge and a possible secondary raw material resource [1]. The characterization and monitoring of these sites are often expensive and cumbersome activities, mainly based on repeated field surveys and sampling campaigns. The present work proposes a cost-effective alternative based on remote sensing. Processing of multispectral and hyperspectral images with the best available techniques can produce multiscale maps useful to investigate and monitor the spatial extent of contamination patterns around mining sites. They can also produce information about stockpiles and the presence of critical raw materials. A limited amount of field sampling and measurements is needed in order to properly calibrate and validate the remote sensing methods [2]. In the present work, the comparison between multispectral Sentinel-2 images [3] and hyperspectral PRISMA [4] processing is presented. The experimentations concentrated on a test site located in southern Italy: the abandoned bauxite mine site of Spinazzola in Alta Murgia National Park (Apulia Region), full of mining residues [5].

2. Materials and Methods

Earth observation data (EO) was selected as an appropriate data source for the raw materials and environmental analysis of bauxite residuals in the chosen area. Multispectral images provided by Copernicus with 10-m spatial resolution (Sensing: 14-09-2020) were

used and compared with hyperspectral images of PRISMA satellite (Sensing: 20-09-2020) with 30-m spatial resolution.

Regarding the field data, three types of field surveys were performed:

- Grab sampling, collected during the field visit to the bauxite mine in July 2020 and used as concentration samples to map metals variability in the selected area by X-ray fluorescence (XRF) chemical analysis at Bologna University.
- The spectroradiometer surveys at two time periods: the first was performed in July 2020 to create a spectral library, after data extraction and preparation; the second was accomplished in June 2021 to validate the results and to check the spectral signature of ground control points (GCP).
- GCP measured by GPS during both the field visits, firstly for images geometry corrections and secondly to validate and check the detected features from the results.

To perform the integration between EO data and in situ measurements (spectroradiometer surveys and field samples), multivariate geostatistical methods were used. The flowchart of the project methods is schematically presented in Figure 1.

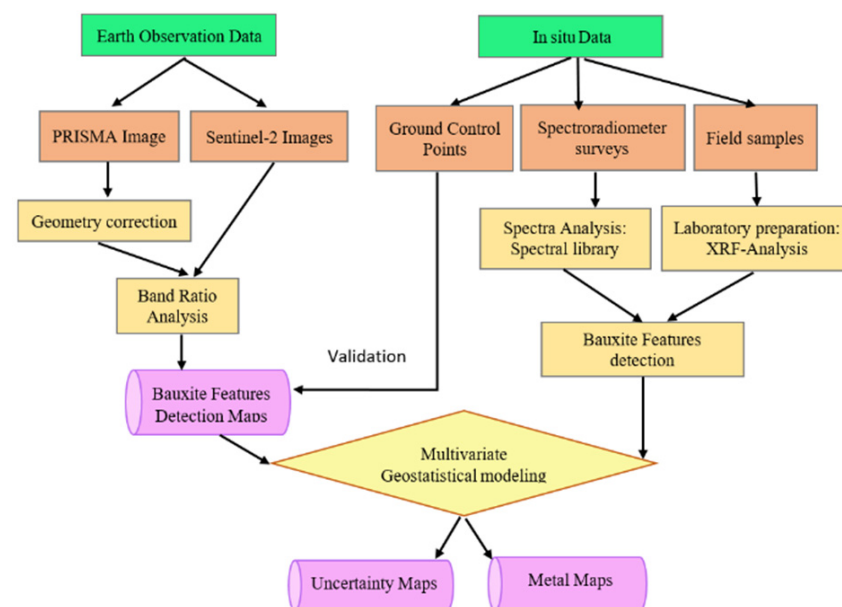


Figure 1. Methodology flowchart.

2.1. Band Ratio Analysis

One of the most common methods in remote sensing studies to recognize different materials in a target area is through the analysis of band ratio images. This procedure is based on the ratio between two or more bands. These ratios can be applied for the “land” areas of interest only, excluding the vegetated, water and cloud areas. Some studies have been done on analysis of band ratio images to distinguish different geological structures and ore deposits [6,7]. This procedure involves the division (or other mathematical formulas) of two or more bands, where the band with high reflectance features of the given material is assigned to the numerator while the other band with high absorption features for the same material is assigned to the denominator [8]. As an example, Table 1 shows band combinations that fall in the wavelength range of Sentinel-2A MSI [7] and the coherent band ratios in PRISMA images tested in the present work.

Table 1. Band ratios of Sentinel-2A used as proxies for mapping different mineralogy.

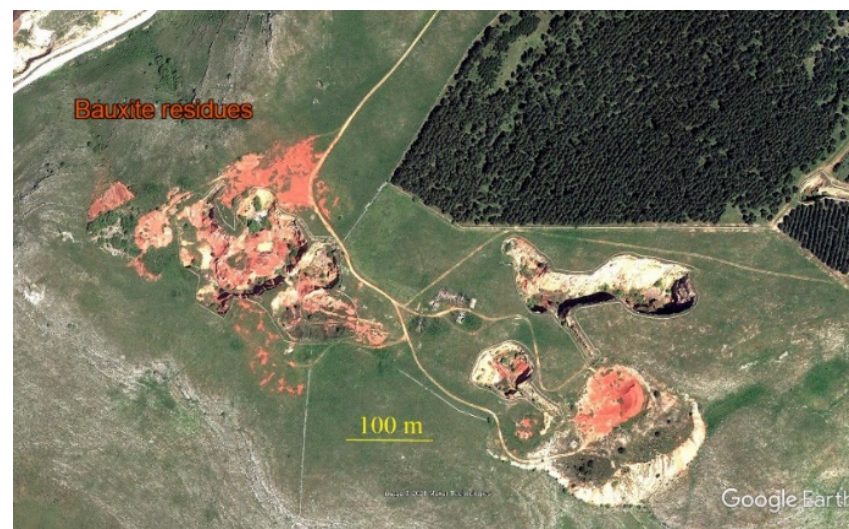
Feature	Sentinel-2A Bands Central Wavelength	PRISMA Bands Central Wavelength
Iron oxides	4 (665 nm)/2 (490 nm)	28 (660 nm)/8 (492 nm)
Laterite	11 (1610 nm)/12 (2190 nm)	105 (1606 nm)/148 (2190 nm)
Ferric oxides	11 (1610 nm)/8 (842 nm)	105 (1606 nm)/46 (844 nm)
Ferrous iron oxides	4 (665 nm)/11 (1610 nm)	28 (660 nm)/105 (1606 nm)
Ferric iron	4 (665 nm)/3 (560 nm)	28 (660 nm)/17 (562 nm)

2.2. Multivariate Geostatistics

Multivariate geostatistical approaches can be used to predict complex variables and to quantify uncertainty in a spatial context and in different fields, such as mineral resources evaluation, reservoir characterization, hydrology, soil and environmental sciences [9–11]. To evaluate the spatial variability of one or more variables (e.g., concentration of elements), the conditional geostatistical simulation can be considered as an appropriate qualitative approach leading to many features, such as the numerical modeling of a dynamic system or the economic optimization of a natural resource [12]. The advantage of the multivariate geostatistical estimation is the possibility of using the spatial correlation between remote sensing data (e.g., band ratios) and in situ samples (metals concentrations) within the coregionalization modeling [13,14]. The results will be metals variability maps, joined with uncertainty maps, showing the dispersion of extracted metals in the selected area (fulfilling the environmental objectives as well). In addition, the range of metals variability can highlight the possible new raw materials sources in the area for future exploration aims.

2.3. The Case Study

In southern Italy, late Cretaceous (late Aptian to early Coniacian) karst bauxite deposits occur in the Abruzzi Mountains in Apulia (Gargano Peninsula and the area around Murge) and Campania (Matese and Caserta Mountains) [15]. The bauxite at Spinazzola is located at latitude 40.986619 and longitude 16.181794 in Apulia (See Figure 2).

**Figure 2.** The bauxite mining residues located in Apulia (Google Earth Image, 12 April 2020).

In the Spinazzola mining site, the bauxite deposit is 20 m thick and preserves both the Valanginian–Cenomanian carbonate footwall and the transgressive, shallow-water Coniacian–Campanian limestones (Calcare di Altamura Formation) at the hanging wall [16]. The only silica-bearing mineral identified within the Spinazzola karst bauxites is kaolin-

ite, while ferruginous nodules are present in soils and residual weathered material as a result of iron migration and accumulation as Al-hematite in kaolinite-rich zones during the ferrolysis stage of oxidation–hydrolysis [17]. The bauxite at Spinazzola is texturally and mineralogically homogeneous and is dominated by boehmite, with lower amounts of hematite and kaolinite and with minor anatase. This means that the major element composition of the bauxite is dominated by SiO_2 , TiO_2 , Al_2O_3 , and Fe_2O_3 .

The red bauxites in the Spinazzola area are formed by a fine-grained kaolinite-rich matrix which embeds iron-rich spheroidal concretions. The genetic model of formation involves the accumulation of clay material in the karst, in situ bauxitization at the expense of the clay and late formation of the concretions in a pedogenic environment [18]. The concretions have a well-developed core formed of Al-hematite and a banded cortex of alternating Al-hematite and boehmite. The mining activity lasted for 28 years, from 1950 to 1978 [5].

3. Field Activities

3.1. Spectroradiometer Survey

The spectral measurements were performed by field spectroradiometer during the field visit of Apulia in nine sampling points (Figure 3). The spectroradiometer used was the SVC HR-768i; it records spectra in the wavelength range between 350 and 2500 nm and is designed for field measurements. Using this instrument allowed us to have high spectral resolution reflectance curves of the investigated materials (specific points of samples) and low noise from the collected data. Besides, a GPS was used to get coordinates, and at the same time, a photo was taken for each sample point. The spectrometry measurements were done to gain the spectrum signature of the materials present in the selected area. This information is useful for the calibration and validation of remote sensing data.



Figure 3. Spectroradiometer measurements of bauxite residues in Apulia.

3.2. Field Sampling

Around 15 in situ samples (grab samples around 200 g each) were taken from the case study area, some from the abandoned excavation areas, some from stockpiles and some extra ones from the surrounding areas without bauxite tracks that were useful as background (Figure 4). Moreover, the control points from the preliminary studies of bauxite residues were checked during the field visit for the geometry correction of the images.



Figure 4. In situ samples (left) taken from different case study areas (numbers in the map, right).

3.3. Field Sampling

Sample analysis was performed at UNIBO labs; all samples were prepared in the Geoengineering and Natural Resources Lab (drying, grinding, quartering and milling). XRF analyses were performed on pressed powder pellets at the Biological, Geological and Environmental Department, University of Bologna. Based on repeated measurements, precision for major elements is always better than 3%, with the exception of P_2O_5 (9%). As for the considered trace elements, precision is better than 10%. A detailed account of the XRF procedure is available in [19]. The concentrations data were used for the metals mapping.

4. Results

4.1. Results of the Band Ratio Analysis

The analysis of different band ratios was performed on both Sentinel-2 and PRISMA images. As can be seen in Figures 5 and 6, PRISMA highlighted new potential bauxite areas within the forest and in the southern part of the forest. These areas are considered as GCPs to check the presence of bauxite. During the second field controls, the reddish soils were indicated within the forest.

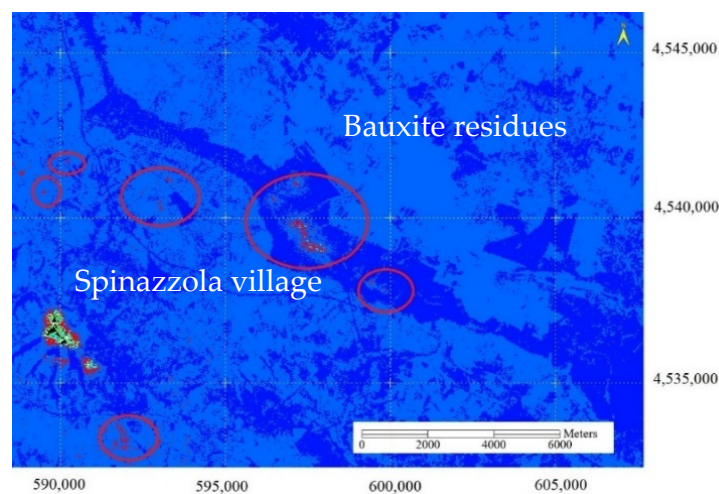


Figure 5. Band ratio analysis (iron oxides: Band28/Band8) detecting bauxite potentials in the Spinazzola rural area (PRISMA).

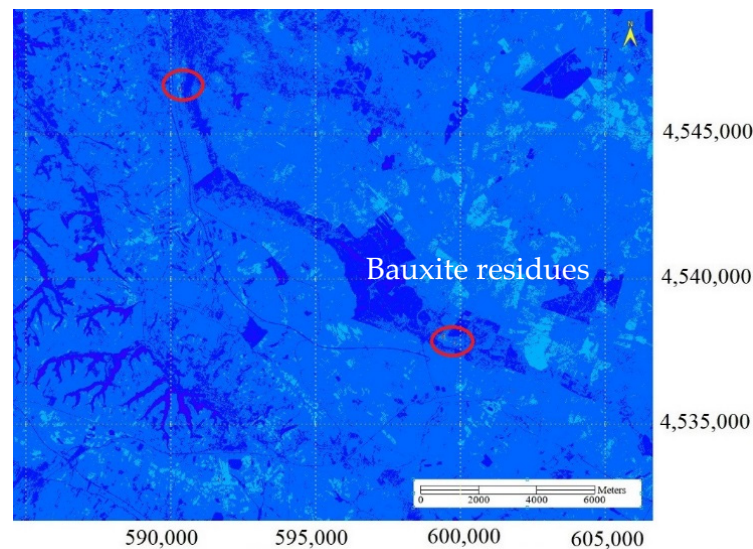


Figure 6. Band ratio analysis (iron oxides: Band28/Band8) detecting elements' variety inside the bauxite residues (PRISMA).

While PRISMA highlighted some bauxite features within the forest, from the Sentinel-2 image band ratios, another additional area was highlighted after the Minervino Murge village. The reddish soil area was present in the highlighted point, and field spectroradiometric surveys were performed (Sample-3). The measured point has a spectrum curve similar to the bauxite residues' spectrum behavior, demonstrated in Figure 7.

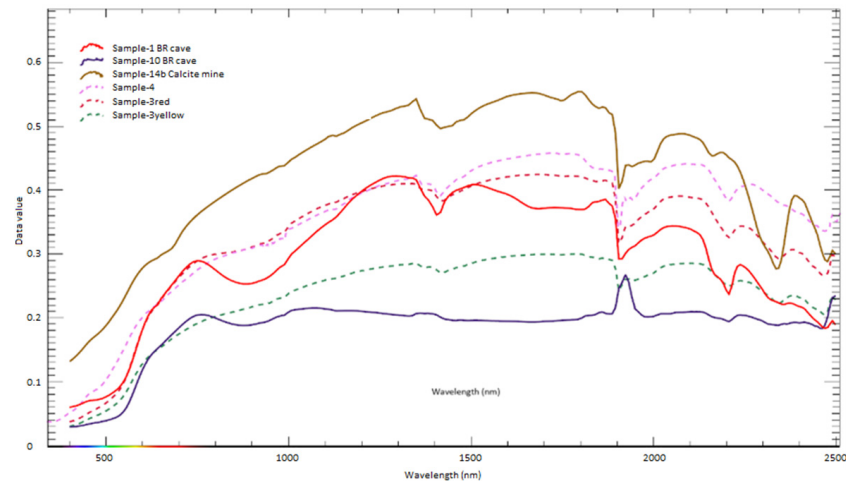


Figure 7. Comparison between spectrum signature of samples from bauxite residues and detected coordinates by PRISMA and Sentinel-2 band ratio analysis.

Moreover, in the southern part of the forest, extra field spectroradiometer surveys were performed from the reddish soil area, which shows the similar spectrum curve to the samples within the bauxite cave (Sample-1 and Sample-4 in Figure 7). The mentioned points were not highlighted in the Sentinel-2 image.

Two ground control points (Sample-3red and Sample-4) have the reflectance curve similar to Sample-1, which is taken from the bauxite residue canyon. Sample-1 has low iron content (13%) but high aluminum content (41%).

4.2. Results of the Multivariate Geostatistical Analysis

Due to the small number of field samples, using the secondary variable from EO data (band ratios) was fundamental for grade mapping. The correlation coefficients between

EO data and concentrations in samples were calculated to find the highest correlation. As a result, the highest coefficient correlations between Al_2O_3 (%) and the band ratios are presented in Table 2.

Table 2. Selected variables and their correlation coefficients for concentration mapping.

Variables	Coefficient Correlation	Reference Image
Al and iron oxides band ratio	0.631	Sentinel-2
Al and iron oxides band ratio	0.595	Prisma

Multivariate geostatistical analysis was performed, first to model the spatial variability among selected variables and then to map aluminum as the main element of the case study area based on previous activities on similar bauxite residues [1,2].

The direct and cross variograms for the variables shown in Table 2 were calculated, and the most coherent model was fitted onto variograms (Figures 8 and 9). The main challenge was the small number of field samples supported by image data (regular and high resolution).

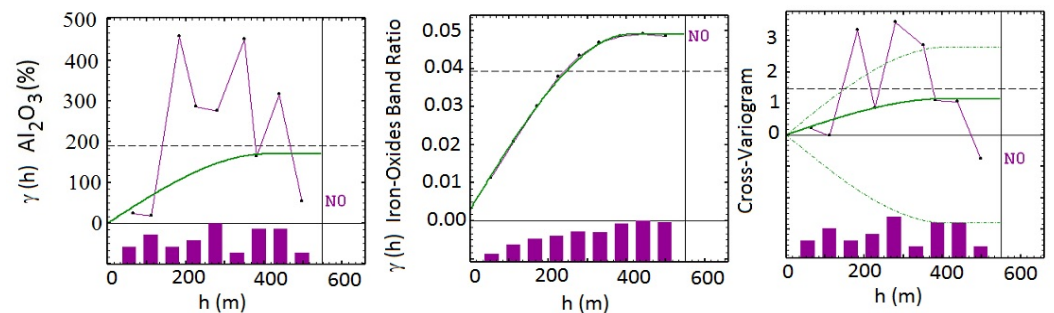


Figure 8. Direct and cross sample variogram (purple) and the fitted model (green line) based on aluminum samples and iron oxides band ratio from PRISMA Image.

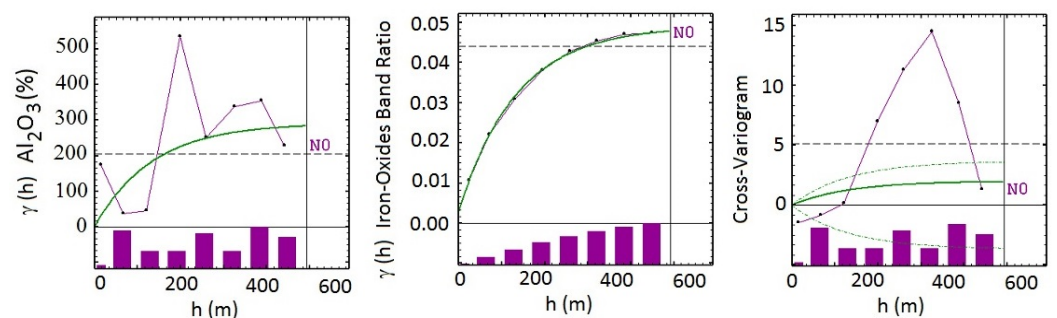


Figure 9. Direct and cross sample variogram (purple) and the fitted model (green line) based on aluminum samples and iron oxides band ratio from Sentinel-2 Image.

4.3. Concentration Mapping

Using the variogram models, collocated co-kriging was performed to map aluminum in the selected area. The same grid size (10 m × 10 m) was used for all results to make the comparison easier. Results show the effect of the different spatial resolutions of satellite images (Figure 10).

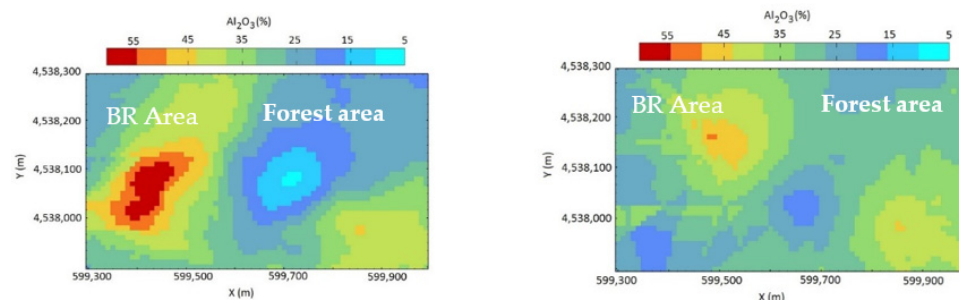


Figure 10. Concentration maps of Al_2O_3 (%) from co-kriging estimation using the data from PRISMA (left) and Sentinel-2 (right).

As shown in Table 2, with higher resolution (in this case, using Sentinel-2), there is higher correlation between band ratios and the selected oxide (Al_2O_3).

5. Discussion and Conclusions

The target of the work was aluminum detection with subsequent evaluation of possible sources and environmental issues. The use of spatial variability analysis through the variogram models and the co-kriging estimation method applied to satellite images provided the possibility of mapping aluminum in the selected case study area, the abandoned bauxite mine of Spinazzola, Apulia (IT). The resulting maps for different satellite images were all created in the grid size $10 \text{ m} \times 10 \text{ m}$ to facilitate the comparisons. Results show the importance of the images' spatial resolutions, providing different secondary variable data sets for each estimation. By increasing the spatial resolution, the correlation between band ratios and the aluminum oxide (Al_2O_3) increased as well. The method used in this work can easily be adapted to any other target raw material or environmental index. There is still a wide space for improvement in this topic for characterization of abandoned mining residues and for exploration attempts of currently unexplored new sources of primary minerals. Many investigations can still be done to unlock the full PRISMA satellite potential for raw materials exploration and recovery integrated into the wide framework of the Copernicus program and its objectives.

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