Integration of Geomatic, Geophysical and Chemical Data in a GIS Environment for Monitoring Contaminated Soils

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Abstract. This paper presents a GIS-based integration of a multidisciplinary dataset concerning a heavy metal contaminated soil. The case study is an area extending for about half a hectare where nearly 600 young trees have been planted to carry out a phytostabilization treatment. Three different plant species have been used for the experiment, lentisk, poplar and oleander, with different characteristics in terms of foliage and mean heights. The area has been monitored by exploiting geomatics, geophysical and chemical techniques, to acquire a comprehensive dataset able to describe the vegetation health status and the soil pollution levels. Low-cost UAV flights, GNSS surveys, and geophysical and chemical investigations have been performed in the area at four different epochs. The different acquisitions were elaborated resulting in specific products (point clouds, DSMs, specific maps) and the related quantitative and qualitative parameters. All the available data have been managed in a GIS project to provide a broad description of the site and to ease the understanding of complex dynamics. The presented analysis belongs to a wider project, aiming at defining monitoring procedures for soils contaminated by heavy metals, using a combination of geomatics, geophysical, and chemical derived parameters. The final purpose will be the definition of algorithms implemented in the GIS environment, specific for different soils, plant species and microbial populations allowing the identification of the optimal conditions for the contaminated site's restoration.

Keywords: GIS · Monitoring · Geomatic survey · UAV · Geophysical survey · Contaminated soil · phytostabilization

1 Introduction

Sardinia (Italy) is the second Italian region in terms of contaminated areas occurrence: in 2018 the Regional Agency for Environmental Protection pointed out a total of 1.411 sites [1]. These have been grouped into different categories, in particular: industrial sites,

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mining sites, landfills, military sites, general sites, fuel-selling sites, and accidental event sites. Nevertheless, only a few of these contaminated sites saw the conclusion of any remediation intervention [1]. The highest number of contaminated areas, equal to 207, is related to mineral sites, namely areas where millions of cubic meters of mineral residuals with high metal concentrations have been released over time. In addition, these areas are usually characterized by rough terrain and are generally hard to access, making impossible their reclamation and restoration over the years. Among the 207 sites, 180 are in southwestern Sardinia (Fig. 1), where indeed minerals like zinc, lead and silver have been mined since the mid-1800s.

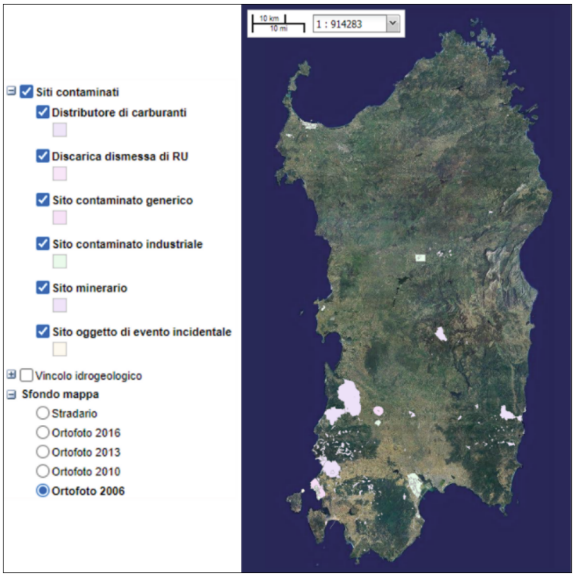

Fig. 1. The cartographic geoportal of the Sardinia region (https://portal.sardegnasira.it/cartografico).

While, from a purely economic point of view, mining sites contributed to the local economy and provided jobs for local people, after the mines' closure during the 1980s-1990s, the areas and the associated buildings were abandoned. This led to a gradual spreading of the metal extraction's wastes, making these lands unsuitable for other activities and potentially dangerous to the population's health. Moreover, all these general considerations should be framed in the regional context, in which mining areas are side-by-side with untouched nature and white beaches of remarkable beauty. In this context, in 2003 Sardinia region promoted a Plan for the reclamation of contaminated sites, although most of these are still pending reclamation [2].

Several approaches and techniques are currently available for the remediation of such sites, involving multidisciplinary expertise such as engineering, geophysics, geotechnics, chemistry, etc. As a result, this kind of analysis commonly requires the proper integration of a significant amount of data, with a challenging interpretation process. In the range

of possible remediation techniques for contaminated sites, phytoremediation is convenient both from an environmental and economic perspective, since it exploits green plants to limit or detoxify contaminants in soil and water [3]. Phytoremediation includes several strategies and procedures to degrade, remove, or immobilize pollutants including degradation (rhizome degradation, phyto-degradation), accumulation (phytoextraction, hemofiltration), dissipation (phytovolatilization), and immobilization (hydraulic control and phytostabilization) [4]. Different mechanisms are exploited by the plants depending on the specific pollutants to reduce their concentrations in soil and water. For example, plants can absorb and accumulate heavy metals in their tissues [5] or degrade organic pollutants [6] to reduce their toxicity level thanks to soil and water resources. Moreover, different plant species can use combinations of reclaim methods for different types, forms, and contamination media. Contaminations of soils, sediments, or muds are treated through phytoextraction, phytodegradation, phytostabilization, rhizodegradation or phytovolatilization [7].

The present description is meant as a general synthetic background as a detailed discussion of phytoremediation techniques is way beyond the scope of this paper. Indeed, this study focuses on the actual management and analysis of the different data sources required for a comprehensive monitoring of the soils' remediation level after these treatments. Consistently, we focus on geomatics, geophysical and chemical data processing, management, and interpretation strategies.

In this context, Geographic Information Systems play a fundamental role since they allow the storage, management and integration of both spatial and non-spatial data (e.g., social, demographic, economic), and they offer many possibilities in terms of processing tools [8, 9]. In fact, in a GIS environment, geospatial information can be processed following a wide range of different operations, which always include merging, querying, and data visualization at different levels of detail [10, 11]. Generally, the analytical processes enabled by GIS systems improve the comprehension of complex dynamics easing decision-making processes. Indeed, when dealing with multidisciplinary studies, spatial information is essential for a proper evaluation of the possible correlation between chemical, physical, and environmental factors, and their impact on environmental sustainability.

The ongoing technological advancements offer several geomatic instruments and techniques able to provide high-resolution digital spatial data [12]. In particular, the monitoring of vegetated areas mainly involves the use of remote sensing techniques to acquire images using sensors (e.g., LiDAR, multispectral, optical cameras) which can be embedded on different platforms such as satellites, aircraft, and drones. Recently, there has been a widespread use of Unmanned Aerial Vehicles (UAVs) due to their flexibility to carry different types of sensors with rapid performance and lower costs than other geomatics techniques [13].

Geophysical analyses allow the assessment of the physical characteristics of the soil at depth (compared with the more standard remote-sensing techniques). These kinds of investigations require the use of specific instruments, such as electromagnetic induction (EMI) tools [14–16].

This paper presents a GIS-based methodology for the integration of data from different geomatics, geophysical and chemical techniques to evaluate the health of plants

in the context of contaminated soils undergoing phytostabilization processes. The presented analysis belongs to a wider project, aiming at defining monitoring procedures for soils contaminated by heavy metals, using a combination of geomatics, geophysical, and chemical-derived parameters. The final purpose is the definition of algorithms implemented in the GIS environment, specific for different soils, plant species and microbial populations allowing the identification of the optimal conditions for the contaminated site's restoration.

The case study consists of a contaminated area of about half a hectare where nearly 600 young trees have been planted to carry out a phytostabilization treatment. Three different plant species have been used for the experiment, lentisk, poplar and oleander, with different characteristics in terms of foliage and mean heights.

Low-cost UAV flights, EMI and chemical surveys have been carried out at different epochs over the area to evaluate the evolution of both the plants' health parameters and the soil's pollution levels. All the available data have been included in a GIS project to find possible correlations and create maps describing the site's characteristics.

2 Monitoring Technologies and Techniques

To gain a multidisciplinary and complete knowledge of contaminated lands and to evaluate the effectiveness of the reclamation approach, different technologies should be mutually used. These include geospatial techniques, and geophysical and chemical investigations [17].

Concerning the first category, GIS and several geomatic techniques should be mentioned. In particular, GIS deserve a separate description as they serve as platforms to merge and jointly analyse all the different kinds of available data [18]. Among the geomatic techniques, Global Navigation Satellite Systems (GNSS) and UAV surveys are usually employed for applications like the one presented in this paper. Data acquired using such instruments provide an accurate metric description of the surveyed areas, from which quantitative parameters can be deduced [13]. On the other hand, qualitative parameters describing the vegetation and the soil are the result of complex geophysical and chemical surveys.

The following paragraphs provide a more detailed description of the mentioned technologies and the commonly implemented procedures for land monitoring activities.

2.1 Geographic Information Systems (GIS)

GIS are likely the major players in multidisciplinary studies involving environmental monitoring since they allow both effective data visualization and a wide range of spatial analysis and tools [10, 19]. Thanks to these instruments, the products of geomatic surveys can be integrated with more specific information, such as geophysical or chemical data, providing comprehensive maps which make the available information easily understandable. This aspect becomes fundamental in the specific context of the considered study, involving different types of technicians and decision-making politics.

In addition, GIS-based spatial analysis allows to easily manage the geomatic products obtaining maps and fundamental parameters describing the vegetated areas [20]. Moreover, these operations can be also carried out by merging or overlaying data acquired

with different instruments, at different spatial scales and relying on different reference systems. This is one of the main potentials of GIS instruments, especially considering the related opportunity of using publicly available datasets such as inventories and indicator maps, to give context and background to more specific information on the study areas. Thus, overall, the use of Geographic Information Systems leads to a smarter and more effective administration of the available resources.

2.2 Geomatic Surveys

Geomatic surveys are designed to acquire all the quantitative information on the soils, and they become essential to ensure that comparisons are accurately performed when combining data from different sources or conducting monitoring operations which extend over time. This is also true considering that, usually, other investigations such as the geophysical soundings should be attributed to specific positions in the final maps, and this is possible only through proper management of the data spatial reference.

Together with the advancement in technologies, nowadays, we are experiencing a shift towards low-cost, user-friendly and more time-efficient geomatic instruments [21]. However, it is not possible to define a single technique and measuring approach usable for different applications or contexts. Indeed, the size of the area, the cost of the surveys, the availability of instruments and tools, and the precision required for the final products are strictly dependent on the specific case [22].

Regardless of this, we will refer to the most common practices employed in contexts like the analysed one. As mentioned, for similar applications, geomatic surveys mainly involve the use of Unmanned Aerial Vehicles. Indeed, drones carrying specific types of sensors are a strategic solution considering cost, usability, and field times. Digital Surface Models (DSMs) and orthophotos can be easily obtained by exploiting large sets of RGB images covering the study area. This three-dimensional information represents the basis for the extraction of the quantitative parameters (trees' heights, crown volume). Furthermore, the use of multispectral and thermal sensors results in different products, such as maps of vegetation indexes describing the state of health of the vegetated areas or the amount of water in the soil. The ordinary processing of the UAV images exploits the Structure from Motion (SfM) algorithm which is currently implemented by open-source software packages following guided workflows [23].

On the other hand, GNSS are fundamental at least as a supporting technique to give the spatial reference for accurate surveys' alignment. In fact, GNSS surveys may involve both the overall study area, meaning the production of Digital Terrain Models (DTMs), or the acquisition of specific points, such as the trees' positions and the coordinates of Ground Control Points (GCPs) for the georeferencing processes. In particular, Real-time Kinematic (RTK) and Network RTK (NRTK) approaches are used to obtain coordinates in real time with centimetre-level accuracy.

2.3 Geophysical Analysis

In this Section, we will refer to the frequency domain electromagnetic (EMI) technique as the geophysical methodology used for the characterization of the subsoil's first few

meters. Indeed, this technique is best suited for sites with terrain roughness like those of our site or for practical considerations.

In this case, during the survey, a time-varying magnetic field is generated by the transmitter; such a primary varying field induces eddy currents in the subsurface, which, in turn, originate a secondary magnetic field that can be recorded by the receiver. Clearly, the recorded signal is a function of the physical parameters of the soil. In particular, the signal at the receiver depends on the electrical resistivity of the subsurface and can be effectively used to reconstruct the 3D volume of that physical property across the investigated domain. In fact, the original transmitted signal consists of several frequency components and the response at each frequency is sensitive to a different depth range.

EMI techniques allow data collection over very large areas, in a very short time, with a high spatial sampling density [24]. On the other hand, EMI measurements are sensitive to electromagnetic noise, and dedicated data processing is required in order to remove, for example, anthropic disturbances. In addition, even if the measurements can be potentially used immediately to infer possible lateral heterogeneities, more advanced inversion techniques are usually required to associate the precise resistivity values to the corresponding depths [25, 26]. However, the translation of the measurements at different frequencies into the resistivity values at different depths is an ill-posed problem and regularization strategies are necessary to tackle the associated non-uniqueness and instability of the solution [27, 28].

EMI surveys result in continuous acquisitions. The inverted resistivity volume can provide information on the spatial distribution of the different lithology/materials, varying water content, and, possibly, the contaminant presence and dynamics (in case the geophysical data are acquired in time-lapse).

2.4 Chemical Investigations

As mentioned, among the wide range of possible reclamation techniques, we dealt with phytostabilization. The concept underlying this treatment is that the existent pollutants are not completely removed, whereas they are constrained, i.e., stabilized, in a reduced layer between the roots and the subsoil. Indeed, thanks to this process, pollutants are prevented from flowing either downward toward the water table, or upward along the plant. This is also the main benefit of phytostabilization since plants are not classified as dangerous wastes [29].

When dealing with this kind of soil treatment, chemical analyses commonly consist of three main steps:

- Soil characterization before planting (T_0) in terms of metal content.
- Planting of the area following defined configurations.
- Sacrifice of sample plants and chemical analysis on the whole plants and their foliage.

In particular, the effectiveness of the treatment can be deduced by comparing values related to the pre-treatment situation with the ones deduced from the sacrifices. Indeed, the chemical analysis provides a quantitative evaluation of the metals' interaction dynamics in the soil-plant system. Thus, it is possible to understand the metabolization status of the different plant systems and the rhizospheric soil.

3 Materials and Methods

3.1 Study Area

The chosen case study is an area of about half a hectare, located in the South of Sardinia, Italy (Fig. 2). The site was involved in a project named "Tecnologie di CARatterizzazione Monitoraggio e Analisi per il ripristino e la bonifica (CARMA)", aiming at the integration of geometric, chemical, and geophysical data in a single workflow to assess the trees' health condition and rates of growth [30]. Indeed, the chosen area suffered from heavy metals contamination (zinc, lead, arsenic, and cadmium) due to the coal spilling in some close extractive areas.

The site was divided into two sectors: most of the area was treated with organic soil conditioners (substrate) while a small part was maintained without any treatments, named the "witness area" (black area in Fig. 2). Then, different species of plants were planted to carry out phytostabilization, thus, to be used as indicators of the soil's state of health after the treatment. In particular, nearly 600 young plants have been placed following a precise configuration along 26 rows with 2–3 m of inter-distance. The geometric setup allowed an efficient management of both the in-situ surveys and the irrigation operations. Poplar, lentisk and oleander have been chosen for the experiment, having different typical characteristics in terms of height and foliage.

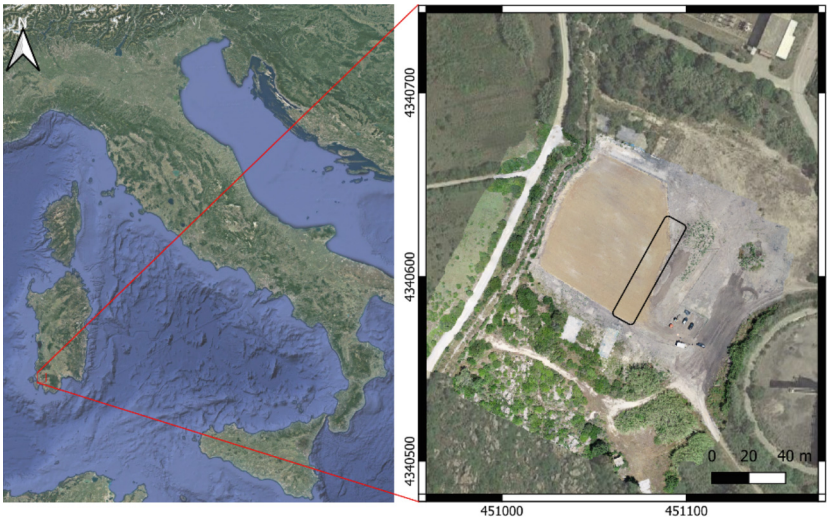

Fig. 2. Study area located in the South of Sardinia, Italy. The black area identifies the sector maintained without any treatments. Base map: Google Satellite. Map generated using Qgis software; coordinates aligned to the ETRS89-ETRF2000-UTM32 reference system (EPSG: 6707).

3.2 Field Surveys and Analysis

The field surveys involved geomatic, geophysical and chemical investigations. Four temporal epochs have been identified for the field operations: hereafter called T_0 to T_4,

where the T_0 epoch refers to the situation before the area plantation, used as a reference for the following evaluations.

Besides the mentioned campaigns, direct measurements of the trees' heights have been performed at epochs T_1, T_2 and T_3 using a metric rod. Table 1 reports the timeline of the performed survey campaigns.

Table 1. Epochs, dates, and survey campaigns performed in the study area.

Epoch	Date	Height measurement	Geomatic survey	Geophysical survey	Chemical analysis
T_0	May 2020		X		X
T_1	August 2020	X	X		X
T_2	January 2021	X	X	X	X
T_3	March 2021	X	X	X	

UAV Surveys

The UAV campaigns involved the use of three different sensors, namely digital RGB cameras, and multispectral/hyperspectral cameras, embedded in different platforms. Table 2 summarizes the main parameters of each UAV flight. Note that, in the case of using different sensors (e.g., RGB and multispectral), multiple columns refer to the same measurement epoch.

For all the UAV survey, overlapping of 80% and 70% forward and side, respectively, were ensured by auto-planning the flights. Furthermore, the accurate georeferencing process was performed by exploiting 8 GCPs. These benchmarks have been surveyed using a Trimble R8 GNSS receiver operating in NRTK mode (SARNET network [31]) obtaining coordinates aligned to the ETRF2000-UTM32N reference system (EPSG: 6707).

Acquired images have been processed using Metashape software (version 2.0.4) [32] following the embedded Structure from Motion workflow. Then, dense point clouds have been elaborated selecting high-quality parameters and the related orthophotos have been produced. Afterwards, the Digital Surface Models processing was carried out using CloudCompare software (version 2.12.14) [33]. In particular, the dense point clouds have been processed through the Rasterize tool choosing 20 cm of pixel dimension, resulting in the associated DSMs.

A filtering operation on the point clouds was necessary to produce the DTMs, leading to the non-ground points removal. This was performed thanks to the Cloth Simulation Filter (CSF) in CloudCompare. Then, the availability of both DSM and DTM related to the same survey epochs allowed the Canopy Height Models (CHMs) computation through a simple operation using the Raster Calculator tool in QGIS software (version 3.34) [34]:

$$\mathrm{CHM} = \mathrm{DSM} - \mathrm{DTM} \tag{1}$$

Table 2. Summary of the sensors' parameters for each UAV flight.

Flight	Sensor, focal length, pixel size, frame dimension	Relative h (m)	GSD (cm)	n. frames	Outputs	Indicators
Zero-RGB	FC6310, 8.8 mm, 2.41 μm, 5472*3648	42	1.0	308	DSM, orthophoto	Trees heights
Zero-Multispectral	Survey 3W_RGN, 3.37 mm, 1.4 μm, 4000*3000	47	1.9	613	NDVI/GNDVI/ CCC maps	NDVI, GNDVI, CCC
1-RGB	FC6310, 8.8 mm, 2.41 μm, 5472*3648	42	1.0	345	DSM, orthophoto	Trees heights
1-Multispectral	Survey 3W_RGN, 3.37 mm, 1.4 μm, 4000*3000	49	2.0	728	NDVI/GNDVI/CCCC maps	NDVI, GNDVI, CCC
2-RGB	FC330, 3.61 mm, 1.56 μm, 4000*3000	30	1.0	313	DSM, orthophoto	Trees heights
3-RGB/Multispectral	RedEdge-M (5 bands), 3.7 μm, 1280*960	57	3.9	189	DSM, orthophoto NDVI/GNDVI/CCC maps	Trees heights, NDVI/GNDVI/CCC

Thereafter, individual trees' heights were obtained from the CHM maps, exploiting a local maxima approach implemented in the GIS environments. This operation allows the identification of the maximum values of CHM pixels within selected trees' neighbourhoods, able to represent the height values.

In order to properly elaborate the vegetation indexes, multispectral acquisitions have been carried out between 9.30 a.m. and 11.30 a.m. The acquired images have been also processed using the SfM algorithm implemented in Metashape software, after properly verifying the camera's calibration. In fact, Metashape enables the calculation of NDVI, and other vegetation indixes based on the multispectral input imagery. Furthermore, the vegetation index formula can be set by the user, thus allowing for great flexibility in data analysis [19]. Raster maps related to three main indexes were obtained using the "*Raster Calculator*" tool, in particular:

- Normalized Difference Vegetation Index (NDVI)
- Green Normalized Difference Vegetation Index (GNDVI)
- Canopy Chlorophyll Content (CCC).

NDVI can represent the vigour of vegetation, regardless of the plant species, with values ranging between 0 and 1 for vegetated and cultivated areas. The GNDVI can be used to identify the presence of water, humidity, and nitrogen absorption. Finally, the CCC index measures the amount of chlorophyll in the vegetation and provides information on the nitrogen amount. In general, there is a direct dependence between the CCC and the vigour of the plants. Equations of the NDVI, GNDVI and CCC are reported in Eqs. (2), (3) and (4):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED}) \big/ (\mathrm{NIR} + \mathrm{RED}) \tag{2}$$

$$\mathrm{GNDVI} = (\mathrm{NIR} - \mathrm{GREEN}) \big/ (\mathrm{NIR} + \mathrm{GREEN}) \tag{3}$$

$$\mathrm{CCC} = \big((\mathrm{NIR} - \mathrm{RE}) \big/ (\mathrm{NIR} + \mathrm{RE})\big) \big/ (\mathrm{NIR} - \mathrm{RED}) \big/ (\mathrm{NIR} + \mathrm{RED}) \tag{4}$$

Geophysical Surveys

The first step of the geophysical investigations involved a preliminary analysis of the site's condition, evaluating possible issues due to the presence of anthropic noise sources. In this regard, the portion of the test area adjacent to the wire fences has been excluded from the measurements. Then, the geophysical data acquisition was performed with the ground-based system GEM-2 [28] and by using 5 different frequencies ranging from 5825 to 80225 Hz. A collection of one sounding every 25 cm was possible. Actually, for effective monitoring of the possible evolution of the electrical resistivity of the subsurface (potentially associated with water content dynamics and pollutant migration), several acquisition campaigns have been performed (a few months apart).

Chemical Investigations

The in-situ chemical analysis performed at epoch T_0 served to verify the preliminary state and homogeneity of the site's contamination level. The effectiveness of the phytostabilization process has been quantified by comparing values related to the untreated soil with the ones related to the conditioned soil.

Pointwise samplings were conducted at defined depths to assess the average level and/or variability of the soil characteristics in terms of pollution. Then, the concentration variation of four analytes (Zinc, Lead, Cadmium and Arsenic) was evaluated from the experimental results at epochs T_1 and T_2. In particular, three biological indicators have been defined, as shown in Eqs. (5).

$$\mathrm{BAC} = \frac{[\mathrm{M_{ep}}]}{[\mathrm{M_s}]};\ \mathrm{BCF} = \frac{[\mathrm{M_r}]}{[\mathrm{M_s}]};\ \mathrm{TF} = \frac{[\mathrm{M_{ep}}]}{[\mathrm{M_r}]} \tag{5}$$

where M_{ep}, M_a, and M_r represent the metal's concentration in the epigean parts, in the soil, and the roots, respectively.

Since the sacrificed samples belong to different plant species, it was also possible to separately define the behaviour of poplar, lentisk and oleander during the treatment. In this regard, "accumulators" and "excluders" were identified as the extremes of the physiological plants' response to the presence of heavy metals in the soil, whereas "indicators" were considered as an intermediate behaviour not completely able to reflect the direct link between absorption and metal tolerance.

3.3 GIS Data Integration

As mentioned, the focus of the presented study consists of integrating all the available data into a GIS project, to provide a comprehensive and multidisciplinary description of the site. All the presented results were obtained using Qgis software.

About this, the first operation involved the joining of the GNSS-derived plants' positions with the related information in terms of plant species, manually acquired on the field (Fig. 3). This was possible thanks to the careful definition of the planting configuration in terms of rows and related id, allowing to match the corresponding data simply.

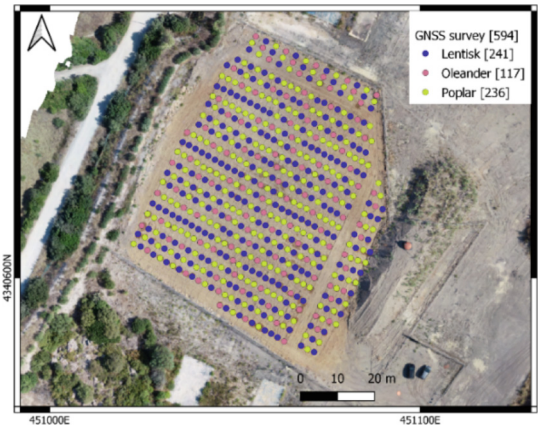

Fig. 3. Qgis Project: GNSS survey on the area and information about the plant species.

Thereafter, all the UAV-derived products were imported into the Qgis project, namely the point clouds (.las), the orthophotos and DSMs (.tif) and the maps obtained from the multispectral acquisitions (.tif).

As mentioned, the extraction of the UAV-derived plants' heights (see Sect. 3.2) has been performed, leading to an automatic matching of the obtained values with the other information. In addition, the available field measurements of the plants' heights (see Sect. 3.2) were associated with the trees' positions and ID, through a GIS-based procedure, allowing the validation of the UAV-derived heights.

The dense geophysical acquisitions (1 point every 25 cm) available as text files have been also imported. Thus, it was possible to view the geophysical data for the whole area and to resample the specific values at the plants' positions.

Concerning the chemical investigations sacrificed plants were identified in the GIS project using their IDs, integrating the attribute table with the related biological indicators. This allowed the possibility to observe the chemical analysis from a pointwise perspective and to produce continuous maps representing the overall trend in the area.

4 Results

This chapter reports the results of the integration of all the data collected in the different survey campaigns with different methodologies, within a comprehensive GIS project. As mentioned, for each type of acquisition or investigation, specific maps and indicators have been obtained. Figure 4 shows an example of a dense point cloud obtained by processing the RGB images acquired during the UAV flight at epoch T_2.



Fig. 4. Example of a UAV point cloud in RGB natural colours, related to T_2 flight.

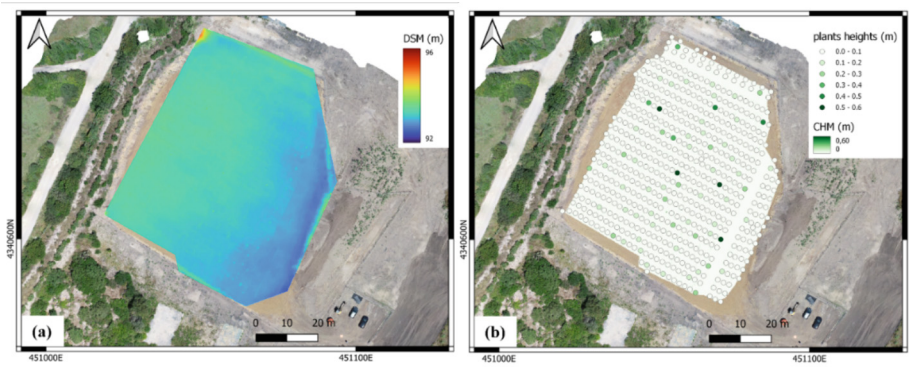

Fig. 5. DSM (a), CHM and extracted plants' heights (m) related to T_2 flight.

The results in terms of Digital Surface Model, related Canopy Height Model and extracted plants' heights are shown in Figs. 5 (a,b), for example case of flight T_2. Note that, since the last two surveys (T_2 and T_3) were performed 8 and 10 months after planting the area, extracted heights exhibit very low values. This made the processing quite challenging, compared to cases where plants are higher and with well-defined crowns. Extracted heights have been compared with the direct in-field measurements for

validation. Nevertheless, this kind of analysis goes beyond the presented study, where the focus is the acquisition of several data sources, that is, the plants' heights at different epochs in this case.

Regarding the analysis of the multispectral acquisitions, obtained maps show the plants' health status in the area handled with substrate compared with the higher stress in the witness area (black area in Fig. 6). However, overall, the vegetation parameters exhibit values below 0.30, mainly due to the low presence of plant biomass. In fact, the reclamation process started a few months before the geomatic surveys, thus resulting in very low plants heights ranging between 10 cm and 140 cm and sometimes with leaf-off conditions. For this reason, the vegetation indexes did not allow the evaluation of the plants' vigour, even considering the last survey epoch T_3. The maps of the NDVI, GNDVI and CCC index related to the T_3 epoch are reported in Figs. 6 (a,b) and Fig. 7 as an example.

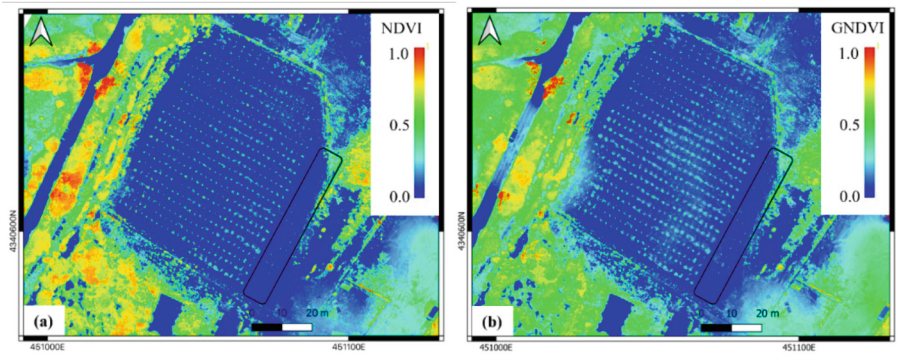

Fig. 6. Map of the NDVI (a) and GNDVI (b) indexes at the T_3 epoch. The black area identifies the witness sector.

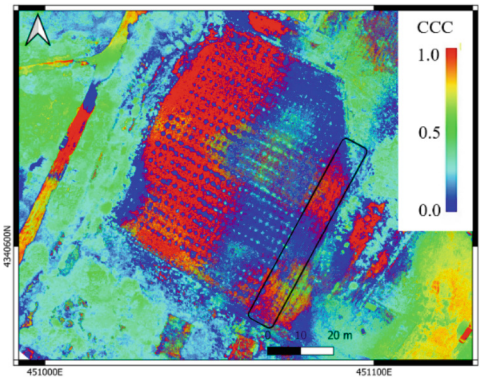

Fig. 7. Map of the CCC index at T_3 epoch. The black area identifies the witness sector.

Figure 8 shows a plan view of the raw data acquired at 15325 Hz during the geophysical surveys. It is clearly visible, not only the NE-SW resistivity trend but also the

more subtle associated with the subsurface heterogeneities. In addition, on the east side, the sharp electrical anomaly due to the unexpected presence of a pipeline can be easily seen. That anomaly was confirmed by direct inspection afterwards.

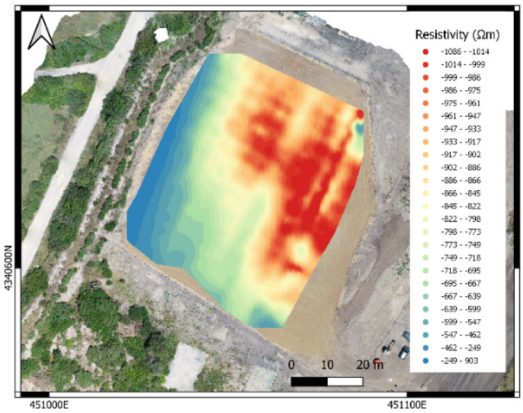

Fig. 8. Map of the geophysical measurements collected at 15325 Hz.

After the data collection and processing, the EMI measurements have been inverted. In this respect, an example of the data inversion is shown in Fig. 9: there, a vertical NE-SW vertical resistivity section is plotted. The actual depth of investigation depends not only on the frequency range but also on the local resistivity values. In particular, less resistive soil prevents to reach deeper layers. That is why the columns in Fig. 9 are not equally long.

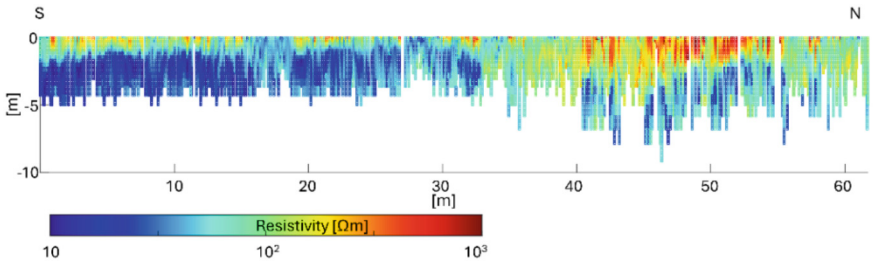

Fig. 9. Vertical section of the geophysical inverted resistivity model.

Tables 3 shows the chemical characterization of the selected samples in terms of biological indicators (see Sect. 3.2), related to epoch T_2. Overall, the accumulation of metals was bound mainly into the root system, without flowing to the stem and leaves, thus without affecting the plants' vigour. However, the different species acted as accumulators, indicators or excluders depending on specific conditions of existence (differences in substrate, presence of microorganism colonies, etc.). Indeed, a multiple

relationship between clone substrate and microorganisms arose, leading to different interactions between plants and pollutants.

Table 3. T_2 Chemical investigation: metals concentrations (mg/kg) of the rhizospheric soil, roots, and stem leaves, in terms of biological indicators.

	Pb			Zn			Cd			As		
Plant ID	BAC	TF	BCF	BAC	TF	BCF	BAC	TF	BCF	BAC	TF	BCF
T1–11 O	0,29	0,25	1,13	0,73	0,62	1,18	2,60	2,00	1,30	0,01	0,01	1,22
F1–10 O	0,57	0,26	2,15	0,62	0,30	2,10	0,87	0,20	4,33	0,01	0,05	0,29
T2–7 P	0,68	0,38	1,80	0,77	0,81	0,95	0,76	0,30	2,52	0,02	0,01	1,46
F10–6 P	0,77	1,06	0,72	1,71	0,41	4,13	5,00	1,00	5,00	0,02	0,02	0,86
T1–5 L	0,28	0,27	1,06	1,20	0,53	2,27	0,63	0,70	0,90	0,02	0,02	1,16
F20–15 L	0,07	0,15	0,47	0,43	0,66	0,65	0,39	0,43	0,91	0,02	0,04	0,91

An example of chemical data examined in the GIS environment is shown in Fig. 10, where the sacrificed plants are displayed together with their associated values of BAC for Pb and Zn analytes, respectively.



Fig. 10. Sacrificed plants: location, and values of BAC indicator for Pb and Zn analytes at T_2.

5 Discussion and Conclusion

This paper presents a comprehensive multidisciplinary analysis of a contaminated area treated through phytostabilization. The general characteristics of these treatments are given to better understand the main purpose of the analysis. Indeed, the chosen case study

is a contaminated area, located in the south of Sardinia in Italy, where phytostabilization has been performed by planting 600 young trees belonging to three different species. The area has been monitored by exploiting geomatics, geophysical and chemical techniques, to acquire a multidisciplinary dataset able to describe the vegetation health status. Indeed, low-cost UAV flights, GNSS surveys, field measurements of the plants' heights, and geophysical and chemical investigations have been performed on the area at 4 different epochs. All the acquisitions were properly elaborated resulting in specific products (point clouds, DSMs, specific maps) and the related quantitative and qualitative parameters.

Throughout the paper, the fundamental role of the GIS is highlighted. Indeed, GIS allowed the combination of both spatial and non-spatial data, thus ensuring the possibility of understanding complex processes including different data sources at different spatial scales. Secondly, they offered the possibility to easily perform a wide range of operations, such as the ones that allow obtaining the main quantitative parameters of plants, i.e., the plants' heights.

Finally, bearing in mind that commonly such studies, like the one presented in this paper, involve not only technicians but also authorities engaged in the decision-making processes, the use of GIS provided maps and reports for straightforward comprehension. Finally, it is worth noticing that the chosen site is part of ongoing research to define a GIS-based algorithm combining geomatic, geophysical and chemical data capable of defining specific procedures of soil reclaim in different conditions.

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