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A GIS based method for soil mapping in Sardinia, Italy: A geomatic approach

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ABSTRACT

A new project was recently initiated for the realization of the "Land Unit and Soil Capability Map of Sardinia" at a scale of 1:50,000 to support land use planning. In this study, we outline the general structure of the project and the methods used in the activities that have been thus far conducted. A GIS approach was used. We used the soil-landscape paradigm for the prediction of soil classes and their spatial distribution or the prediction of soil properties based on landscape features. The work is divided into two main phases. In the first phase, the available digital data on land cover, geology and topography were processed and classified according to their influence on weathering processes and soil properties. The methods used in the interpretation are based on consolidated and generalized knowledge about the influence of geology, topography and land cover on soil properties. The existing soil data (areal and point data) were collected, reviewed, validated and standardized according to international and national guidelines. Point data considered to be usable were input into a specific database created for the project. Using expert interpretation, all digital data were merged to produce a first draft of the Land Unit Map. During the second phase, this map will be implemented with the existing soil data and verified in the field if also needed with new soil data collection, and the final Land Unit Map will be produced. The Land Unit and Soil Capability Map will be produced by classifying the land units using a reference matching table of land capability classes created for this project.

1. Introduction

The island of Sardinia (Italy), because of its particular geographical position and its extreme climatic events, such as droughts and flash floods, can be considered a representative area for the typical environmental problems of the Mediterranean region (Mairota et al., 1997). In particular, the landscape morphology and the climate result in the island soil's being notably fragile and extremely sensitive to degradation under any land use change that does not properly take into account the soil's qualities and limitations (Vacca et al., 2002). Because of these issues, the problem of soil degradation, defined as the loss of soil or soil quality for specific functions (Blum, 2008), is of great concern to the island administration, and the subject has been widely investigated in recent decades within the framework of national and international studies and projects (Aru et al., 2006). The findings of these studies have indicated that anthropogenic factors, associated with agriculture, forestry, livestock production, industry and urbanization, are the leading cause of soil degradation (Aru et al., 2006). Therefore, land planning at different levels is considered to be the key issue in the prevention and mitigation of soil degradation on the island of Sardinia (Vacca and Vacca, 2001). For this purpose, the planning process must be based on an accurate inventory of the natural resources, including soil, soil evaluation and definitions of alternative, suitable uses (Vacca et al., 2002).

Currently, the only available regional soil inventories are the Soil Map of Sardinia (Aru et al., 1990), at scale 1:250,000, the Ecopedological Map of Sardinia (Madrau et al., 2006), at scale 1:250,000, and the Soil Map of the Irrigable Areas of Sardinia (Arangino et al., 1986), at scale 1:100,000. The scale of these three soil maps is obviously not adequate for local land planning strategies. Moreover,

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a large amount of soil data, mostly stored on paper and not always freely available, is scattered among public offices and universities (Vacca, 1996).

The land unit (LU), considered as a homogeneous tract of land at the scale at issue, provides a basis for mapping and transferring landscape knowledge, via evaluation, to application (Zonneveld, 1989). Consequently, the LU concept is widely used for land use management and planning (Bastian, 2000; Şahin and Bekişoglu, 2009; Lisio and Russo, 2010; Papadimitriou, 2012). In LU classification, the soil data are as important as geology, landform, climate and vegetation.

The Land capability classification (LCC) (Klingebiel and Montgomery, 1961) is a system originally used for grouping soils primarily on the basis of their capability to produce common cultivated crops and pasture plants without deteriorating over a long period of time. Instead, over time, the LCC has been increasingly used for territorial programming and planning based on a wider spatial scale of reference than that of individual farms (Costantini, 2009). The LCC provides a scientific method for land conservation and proper land use planning on a long-term sustainable basis, without permanent damage through erosion and other causes, and can be considered the basis for any land use management program.

Geographical information systems (GIS) provide a powerful tool for geo-environmental evaluation, and their application in support of land use planning is acquiring increasing importance (Harris and Elmes, 1993; Jacobs, 2000; Nour, 2011).

The land use planning activity of the Regional Administration of Sardinia (RAS) has undergone a substantial change after the approval, in 2006, of the Regional Landscape Plan (RLP) (Zoppi and Lai, 2010). The RLP, controlled by the National Code of Cultural Heritage and Landscape, establishes the directions for any land use planning in Sardinia and requires that pre-existing sectoral, province and city plans, as well as plans for protected areas, have to be changed to comply with these directives (Zoppi and Lai, 2013).

In the RLP, the soil is specifically considered one of the main landscape components (Regione Autonoma della Sardegna, 2006). Indeed, in the RLP guidelines (Regione Autonoma della Sardegna, 2008), a soil survey of the whole communal territory is required (at the suggested reference scale of 1:10,000). Moreover, LU and LCC maps are explicitly required, and the adoption of a single regional reference legend for these maps is strongly recommended.

The Planning Department of the RAS has recently realized the need for specific knowledge and tools to support land use planning according to the RLP rules. Consequently, a new project for the creation of a “Land Unit and Soil Capability Map of Sardinia”, at a scale of 1:50,000, was recently initiated.

Bearing in mind the above mentioned needs of the RAS and that the LU concept requires the integration of several environmental attributes, we decided to develop a cost-effective approach in which digital environmental data along with soil data are used to delineate LU in a GIS environment. A LU is defined in this study as a homogeneous spatial area in terms of soil, geological substratum, landform and land cover. In this paper, we present the GIS-based approach used to build the “Land Unit and Soil Capability Map of Sardinia” at a scale of 1:50,000, and we discuss the methodology used to delineate the LU, to validate the existing soil data and to create the soil database.

2. Methodology

2.1. The soil-landscape paradigm

Soils are formed in an interaction traditionally described by five factors: parent material, relief, time, climate, and organisms (Jenny, 1941). The complex interactions among these factors take place following repetitive patterns that may be observed at different scales, leading to the formation of repetitive combinations. This is the basis for the definition, identification and mapping of soils (Soil Survey Division Staff, 1993). Indeed, for the most part, soils are the same wherever all the five factors are the same. Therefore, under similar environments in different places, soils are similar. This regularity permits the prediction of the location of many different types of soils. In these terms, the local patterns of topography or relief, parent material, and time, along with their relationships to vegetation and microclimate, can be used to predict the types of soils in small areas (Soil Survey Division Staff, 1993). The soil-landscape paradigm can be used to predict soil classes and their spatial distribution or to predict soil properties, as based on landscape features (Hudson, 1992). Based on these principles, during the first phase of this project, the existing data on the fundamental factors of soil formation were obtained and used to produce a first draft of the Land Unit Map of Sardinia lacking soil information.

2.2. The detailed workflow of the project

The work was divided into two main phases (Fig. 1), and a GIS approach was used. ArcGIS 10 Desktop version (ESRI, Redmond, USA) was used as the main GIS environment. The processing of the digital elevation model (DEM) data for the morphometric analysis was conducted by means of SAGA (System for Automated Geoscientific Analyses) FOSS (Free Open Source Software), developed by the team headed by J. Bohner and O. Conrad at the Department of Physical Geography at the University of Hamburg, Germany. The Eliminate and Smooth tools of the Terranova Sharc 4.3 GIS suite (Terranova, Sistemi Informativi Territoriali, Urbania, Italy) were used to create the first draft of the Land Unit Map.

The following activities are anticipated in the first phase of the project (Fig. 1):

- Merging and reclassification of the original land cover units, as well as of the original geological units, into new units that are relevant to soil formation.
- Production of a landform map, whose units are relevant to soil formation, using the regional DEM, driven by knowledge of the regional soil distribution model, via a semi-automatic classification.
- Overlaying of the new three layers (parent materials, landforms and land cover) into the first draft of the Land Unit Map.
- Creation of a soil database.
- Collection, evaluation, standardization and inputting into the database of the existing soil data (both maps and punctual data).

The following activities are anticipated in the second phase of the project (Fig. 1):

- Linking of the soil database to the first draft of the Land Unit Map, by means of expert interpretation, to produce the second draft of the Land Unit Map, which contains soil information.
- Verification in the field, modification and implementation with new soil data as necessary, which will be input into the soil database, of the second draft of the Land Unit Map and production of the final Land Unit Map.
- Production of the Land Unit and Soil Capability Map by classifying the LUs by means of a reference matching table of Land Capability classes created on purpose for this project. The legend of this map will be divided into three main sections, called Land Unit, Soil and Soil Capability, respectively. Each section will be divided into several parts (columns of the legend) (Table 1).

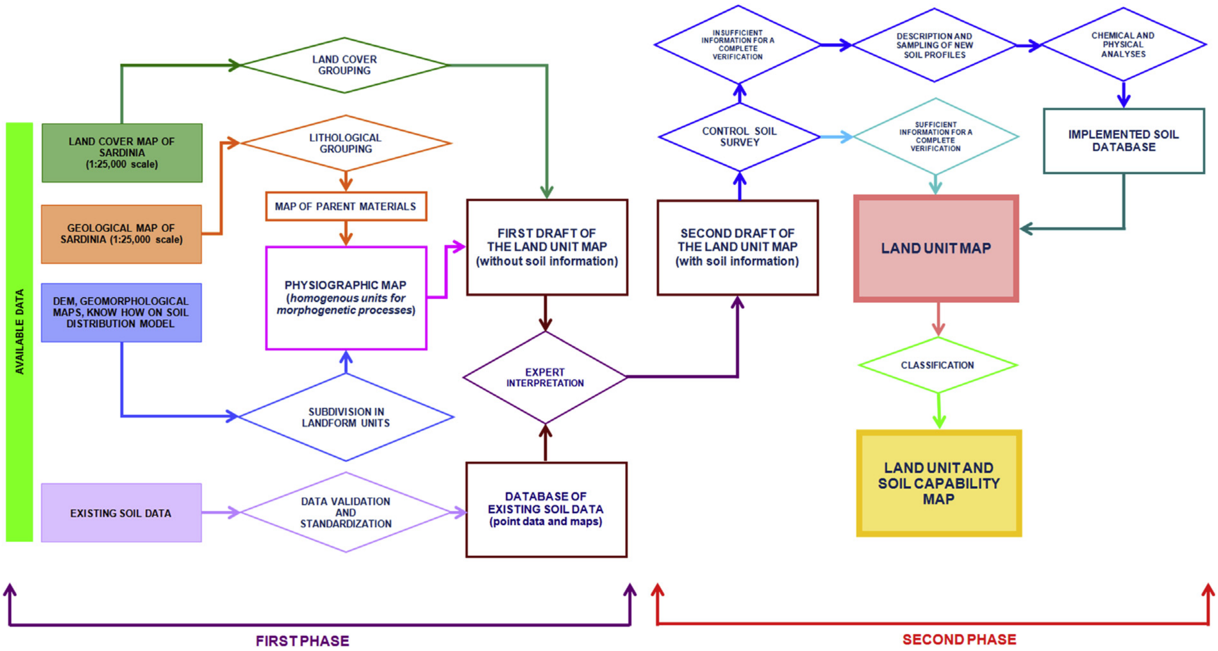

Fig. 1. Workflow of the project.

2.3. *The used existing data*

The RAS holds a large cartographic collection, both in digital format and hard copy. Many of these data are publically distributed via its Internet portal (http://www.sardegnageoportale.it/). According to the GIS approach of the project, only the digital data have been used. These data are as follows:

- A land cover map of Sardinia, created in 2008 with the CORINE Land Cover V level legend was used. It is in ESRI format, and it is composed of 224,061 polygons with 71 unique values. This map is an updating of the previous land cover maps created since 1996 in the CORINE EU Project (http://www.eea.europa.eu/publications/COR0-landcover). The classification is based on the photo interpretation of aerial photographs acquired in 2006, satellite IKONOS images acquired in 2005 and 2006, and ancillary topographic and thematic available data.
- A geological map of Sardinia at a scale of 1:25,000, which was created in 2008 by the Regional Geological Agency PROGEMISA was used. The map may be considered the most advanced geological data available for the whole island. This map, only available on the Web (http://www.sardegnageoportale.it/index.php?xsl=1598&s=141554&v=2&c=8831&t=1) (official hard copies have not been made), was created with the aim to supply geological information to the Sardinian municipalities for urban and landscape planning purposes. It was created by collecting all the available basic geological maps of the entire Sardinia, defining a common legend (with more than 600 formations and more second-rank lithostratigraphic units) and with new surveys of the Quaternary deposits (based both on field mapping and on geological interpretation on aerial photos). There are general sources for the map: i) the recent geological maps created in the last 15 years during the CARG Project/Italian geological mapping at the 1:50,000 scale, based on 1:10,000 scale mapping and ii) several geological surveys performed by PROGEMISA during approximately the last 30 years, for many different purposes and at many different scales. In the map, both bedrock and superficial Quaternary deposits are distinguished. The rocks are distinguished using the lithostratigraphic criteria. Thus, there are formations, magmatic intrusive units and metamorphic complexes. Generally, Quaternary deposits are mapped as unconformity-bounded stratigraphic units (UBSU) when their thickness overcomes one/two meters on average for the same outcrop. Alluvial deposits, whatever their age (Pleistocene or Holocene), are all mapped. However, outcrops of deposits largely related to gravity-driven emplacement (colluvia, scree, slope deposits, etc.) less than 1–2 m thick were generally not mapped. All the data are reported in a dedicated geodatabase. The database contains 60,171 polygons representing 895 unique values (i.e., the lithostratigraphic units).
- A DEM, year 2011, distributed in ESRI GRID format, with 10-m pixel pitch and a vertical and horizontal accuracy of 2.5 m was used. It is a digital terrain model (DTM) generated by the RAS using the 3D Analyst and Spatial Analyst extensions of ArcGIS 10.0 (ESRI, Redmond, USA). The layers Contour_Lines and Elevation_Points of the 1:10,000 scale geographic database (GeoDB 10k) of the RAS were analyzed as source data. A triangulated irregular network (TIN) was generated and subsequently transformed into a raster ESRI GRID format. The sea pixels were assigned a NoData value. The DTM is georeferenced according to the WGS84 (EPSG code: 32632) datum and UTM projection system.
- Orthophotos, coming from several air surveys of different periods and at different spatial resolutions (Table 2), were used. Each orthophoto mosaic is georeferenced according to the WGS84 (EPSG code: 32632) datum and UTM projection system.

Moreover, soil data (point data and maps), mostly stored on paper and scattered among public offices and universities, but not always freely available, have been used as well.

3. Results

The integrated work among the various partners has led thus far to the completion of the first phase of the project.

Table 1
Frame of the legend of the land unit and soil capability map of Sardinia.

Section	Column of the legend and description of content
Land Unit	1st column, identification code
	2nd column, description of parent material
	3rd column, description of landforms
	4th column, description of land cover
Soil	5th column, description of main morphological and physicochemical properties
	6th column, taxonomic classification according to Soil Survey Staff (2010)
	7th column, taxonomic classification according to IUSS Working Group WRB (2007)
	8th column, typology and value according to the RLP Guidelines
Soil Capability	9th column, subclass of soil capability
	10th column, main limitations
	11th column, suggested practices of soil conservation

3.1. Land cover map

In regards to land cover, the 71 classes of the CORINE Land Cover V level legend were reduced to 37 classes (Table 3) according to their pedogenetic influence, mainly regarding the distribution and supply of soil nutrients by directly altering soil properties and by influencing biological transformations in the rooting zone, organic matter and nitrogen content in the top soil, bulk density, porosity, aggregate stability and soil erosion (Vacca, 2000; Khresat et al., 2008; Kocygit and Demirci, 2012; Muñoz-Rojas et al., 2012). Different levels of the CORINE legend were used: the I level for 1 class, the II level for 3 classes, the III level for 21 classes, the IV level for 9 classes and the V level for 3 classes. In one case, for both the IV and V levels, two different classes of the CORINE legend were merged together. Following this, the land cover map of Sardinia has undergone a generalization based on thematic attribute criterion. The new land cover map, in shape format, is composed of 137,735 features classified into 37 unique values. Each unit of this map represents classes of land cover that have a similar influence on soil (Fig. 2).

Table 3
Units of the land cover map.

Code	Description
1.1.1	Continuous urban fabric
1.1.2	Discontinuous urban fabric
1.2	Industrial, commercial and transport units
1.3	Mine, dump and construction sites
1.4.1	Green urban areas
1.4.2	Sport and leisure facilities
2.1.1	Non-irrigated arable land
2.1.2.1 and 2.1.2.2	Permanently irrigated arable land and Nurseries
2.1.2.3	Greenhouses
2.1.3	Rice fields
2.2.1	Vineyards
2.2.2	Fruit trees and berry plantations
2.2.3	Olive groves
2.3.1	Pastures
2.4.1	Annual crops associated with permanent crops
2.4.2	Complex cultivation patterns
2.4.3	Land principally occupied by agriculture, with significant areas of natural vegetation
2.4.4	Agro-forestry areas
3.1.1.1	Broad-leaved forest
3.1.1.2.1	Poplar, willow and eucalyptus groves
3.1.1.2.2	Cork oak forest
3.1.1.2.3 and 3.1.1.2.4	Chestnut groves and other arboriculture types with broad-leaved trees
3.1.2	Coniferous forest
3.1.3	Mixed forest
3.2.1	Natural grasslands
3.2.2.1	Shrubs and bushes
3.2.2.2	Bank vegetation without trees
3.2.3.1	Mediterranean maquis
3.2.3.2	Garrigue
3.2.4.1	Natural young stands
3.2.4.2	Artificial young stands
3.3.1	Beaches, dunes and sand plains
3.3.2	Bare rocks
3.3.3	Sparsely vegetated areas
4.1.1	Inland marches
4.2	Coastal wetlands
5	Water bodies

3.2. Map of parent materials

Using the geological map of Sardinia at the 1:25,000 scale, a map of parent materials with 58 new units (Table 4) was derived according to their influence on the weathering processes and on the soil properties. Lithology was the main criteria used for the grouping, but genetic characters, texture, structure, composition and age were used as well (Birkeland, 1999; Brady and Weil, 2008; Sierra et al., 2009; Buol et al., 2011).

Genetic criteria were used for a first level to differentiate the whole legend in rocks belonging to the Paleozoic metamorphic basement, the Late-Variscan magmatic complex, the post-Variscan volcanic successions and the post-Variscan sedimentary successions. Overall lithology, the other criteria were applied inside these large groups. In the magmatic intrusive units, the lithology is easily deducible because of their compositional widespread homogeneity. In sedimentary and volcanic successions, the single units do not necessarily consist of rocks with the same lithotypes. In many cases, different lithotypes are represented in minor lithostratigraphic units (i.e., members), often in lithofacies (e.g., "metalimestone" in the Black Silurian shales cropping out in the Variscan basement). The expertise of the involved researchers has aided in the

Table 2
Details on the used orthophotos.

Name	Description	File format	Geometric resolution	Radiometric resolution	Positional accuracy
Ortofoto 1954 – mosaico	Orthophoto mosaic of Sardinia at 1:25,000 scale, created from digital scanning (800 dpi, 8 bit) of frames acquired in 1954 and 1955 by aerial surveys	TIFF	5 m	8 bit	5 m
Ortofoto 1968 – mosaico	Orthophoto mosaic of Sardinia at 1:10,000 scale, created from digital scanning (1200 dpi, 8 bit) of frames acquired in 1967 and 1968 by EIRA aerial surveys	ECW	6 m	8 bit	6 m
Ortofoto 2000 IT – mosaico	Orthophoto mosaic of Sardinia at 1:10,000 scale, created from digital ITALIA2000 aerial surveys made in 1998 and 1999	ECW	1 m	24 bit	10 m
Ortofoto 2003 AGEA – mosaico	Orthophoto mosaic of Sardinia at 1:10,000 scale, created from digital AGEA aerial surveys made in 2000	ECW	1 m	24 bit	10 m
Ortofoto 2006 Terraitaly – mosaico	Orthophoto mosaic of Sardinia at 1:10,000 scale, created from digital aerial surveys made in 2006	ECW	0.5 m	24 bit	10 m
Ortofoto 2008 – mosaico	Orthophoto mosaic of the coastal belt of Sardinia at 1:2000 scale, created from digital aerial surveys made in 2006 and 2008	ECW	0.2 m	8 bit	0.5 m

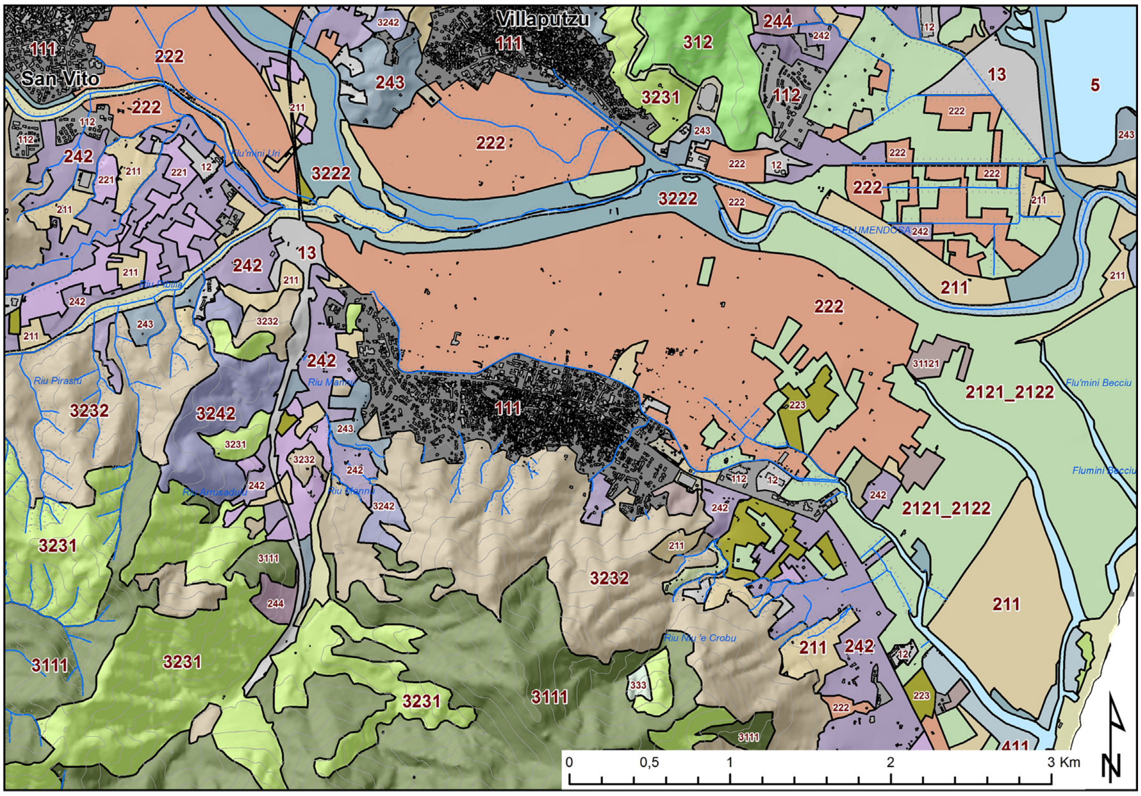

Fig. 2. Extract of the land cover map. Codes are those of Table 3.

recognition of different lithotypes cropping out in different places in the few cases that this difference is not explicitly reported in the geological map.

Compositional criteria have largely been used to distinguish rocks in the volcanic successions, in addition to those inside the Paleozoic metamorphic basement (e.g., rhyolite versus andesite, etc.).

Textural criteria were applied in different ways, being this feature often, but not always, linked to composition. For example, Upper Ordovician quartzites were distinguished from quartzitic metasandstones of the same age because the first are more resistant to weathering than the second ones, and this difference influences their contributions to soil formation. Rock texture has often been used as a secondary criterion in magmatic rocks, e.g., foliation in acidic to intermediate plutonites or grain size in acid granitoids.

In addition, the depositional environment is a useful criterion to overcome some ambiguities not resolved by lithological criteria because it can suggest differences in composition and texture in the same lithotype (Prothero, 1990; Miall, 1997). For instance, aeolian sandstones are different in composition and texture from littoral arenites.

The age criterion was used along with the other criteria in grouping the Quaternary deposits because of its primary role in soil development and evolution (Carboni et al., 2006). It is important to highlight that different considerations must be applied depending on the type of deposit. For alluvial deposits, whatever their age, their contribution to soil formation is unrelated to their bedrock, and thus, they must be considered as lithostratigraphic units. Instead, colluvia, slope deposits, and other such structures change their lithology and composition according to the bedrock on which they lay on. Thus, they must be differentiated according to this feature.

The available soil data have been used to verify the grouping process. Following the grouping result, the geological map of Sardinia has undergone a generalization based on thematic attribute criterion. The outcome is a map of parent materials (Fig. 3), in shape format, composed of 60,171 polygons classified into 58 unique values.

3.3. Landform map

The topography was classified into terrain types on the basis of two morphometric indices: slope and curvature (sensu Zevenbergen and Thorne, 1987). The method considers these two morphometric parameters as they can indicate, particularly the curvature, whether a cell is prone to accumulate water (Shary et al., 2002; MacMilland and Shary, 2009). In this context, curvature can be of great value for describing and delineating the areas with potential sediment accumulation and soil development and those prone to soil erosion. The used methodology simplifies those proposed by Iwahashi and Pike (2007) and by Gorini (2009) for landform classification. Only slope and curvature were considered in the classification. Aspect, surface roughness and elevation above sea level were not taken into consideration because they strongly influence land cover (Solon et al., 2012; Wondie et al., 2012) and, consequently, their influence on soils is already indirectly present in the land cover map. Four classes of slope, based on the regional soil distribution model (Arangino et al., 1986; Aru et al., 1990; Madrau et al., 2006; Marrone et al., 2008), were used: class 0 for land with a slope lower than 2.5%, class 1 for land with a slope ranging from 2.5 to 15%; class 2 for land with a slope ranging from 15 to 35% and class 3 for land with a slope higher than 35%. Classes 1 to 3 were further subdivided according to the curvature (+ for convex areas and − for concave areas). The result is a 7-classes legend ranging from −3 (strongly sloping and concave areas) to +3 (strongly

Table 4
Units of the map of parent materials.

Code	Description
LRD	Rhyolitic-dacitic lava flows and dikes
LIB	Basic and intermediate lava flows
IGN	Rhyolitic to dacitic welded pyroclastic flows
BEP	Pyroclastic breccias, epiclastic conglomerates and breccias
LAC	Fluvio-lacustrine deposits with interbedded tuffs and epiclastites
PRL	Unwelded pyroclastites with interbedded epiclastites
CPA	Polygenic conglomerates with continental and transitional sandstones
CQL	Cemented conglomerates with quartz and black cherts and quartzitic sandstones
CDL	Limestones and dolostones
MRN	Marls, marly and nodular limestones
AMC	Intercalations of clays, marls, limestones and sandstones
AEO	Aeolian sandstones
RMF	Intermediate to acid foliated plutonites, gneiss and "porphyroids"
FAP	Pegmatite-aplite dikes and their metamorphic products
MCS	Micaschists
MRM	Marbles
MCN	Marly and nodular metalimestones
MVA	Acid and intermediate metavulcanites and their metamorphic products
MVB	Basic metaplutonites, intermediate and basic metavulcanites and their metamorphic products
FIL	Slates and metapelites (metargillites and metasiltites)
QTZ	Quartz dikes, quarzites, black cherts, silicizations
MTA	Metasandstones (metaquartzarenites, metarkose, metagraywacke)
MCG	Metaconglomerates and metabreccias
PIB	Intermediate to basic plutonites and dikes
BRI	Intrusive breccias
PAI	Fine- to coarse-grained intermediate to acid porphyric or inequigranular plutonites
PAE	Fine- to coarse-grained intermediate to acid equigranular plutonites
PLF	Fine grained intermediate to acid plutonites
MIG	Plutonites without textural description and migmatites
BSP	"Basaltic lava flows" l.s.
BBP	Breccias and cones of basaltic scoria
SSP	Silica-undersaturated and saturated lava flows
BXT	Bauxite and residual clays
CTN	Limestones (often with subordinate terrigenous material)
ATN	Transitional sandstones and sands
MAN	Intercalations of marls, sandy and silty marls, marly limestones, sandstones (marly-arenaceous series Auct.)
ACN	Red clays with subordinate conglomerates
DAN	Anthropic deposits
DCO	Holocene colluvial deposits (to be differentiated according to their lithological composition)
DVO	Slope and active landslide deposits (to be differentiated according to their lithological composition)
DFO	Holocene-stabilized landslide deposits (to be differentiated according to their lithological composition)
ARO	Recent alluvial deposits (without lithological distinction)
AGO	Recent gravelly alluvial deposits
ASO	Recent sandy alluvial deposits
ALO	Recent silty-clayey alluvial deposits
ATO	Holocene terraced alluvial deposits (without lithological distinction)
ATG	Holocene terraced gravelly alluvial deposits
ATS	Holocene terraced sandy deposits
ATL	Holocene terraced silty-clayey alluvial deposits
CAO	Holocene limestones
SLO	Holocene lacustrine deposits
LIO	Holocene littoral sands
DEO	Holocene aeolian deposits
SAO	Holocene old beach deposits
DVP	Pleistocene slope and landslide deposits
DAP	Pleistocene alluvial deposits
DSP	Pleistocene beach deposits ("Panchina Tirreniana" Auct.)
CPM	? Middle Pleistocene colluvial deposits

sloping and convex areas) with zero as the central value. A broad geomorphological description is given for each class (Table 5).

The methodology was applied to the datasets in raster format. The first step was the extraction of the two morphometric maps from the DEM: slope and curvature maps. The resulting datasets were reclassified according to the studied legend. The second step was the application of a map algebra multiplication to the resulting datasets ($M = S^*C$, where M is the landform map, S is the slope map and C is the curvature map). The output of this arithmetic expression is a map representing, for each pixel, the attribution to one of the 8 classes: 4 positive and 4 negative, with an increasing slope. The last step was the reclassification of the pixels with values -1 and $+1$ into a class with value 0. This class represents the nearly flat areas and simplifies the meaning of these landforms. Fig. 4 shows an extract of the landform map.

3.4. First draft of the Land Unit Map

Several Spatial Analysis utilities were used to produce the first draft of the Land Unit Map. As a first step, the landform raster data were generalized by filtering it using the Majority Filter operator of ArcGIS. This approach was employed to curtail the number of unwanted features, such as single pixels or small pixel agglomerates, with an area smaller than 5 ha, which is considered to be the minimal mapping unit according to the final scale of the map (1:50,000). After some tests, the Majority replacement threshold and the eight cells kernel were set as input parameters to minimize the corruption of cellular spatial patterns. This operation was used repeatedly until the data did not assume a stable connotation (Behrens et al., 2008). The best generalization result was obtained after 21 repeated passages of the filter.

As a second step, the raster data were converted into vector data (shapefile format) by using the ESRI Spatial Analyst Raster to Polygon tool without smoothing the edge of the features. Because of this spatial operation, a large number of small clusters of polygons still burdened the output layer. This issue affected the ease of management of the layer within the computer file. Therefore, a further vectorial generalization operation was performed using the Eliminate tool included in the Sharc Terranova GIS suite. This operation aims to eliminate polygons smaller than a threshold fixed by the operator by merging them into the wider adjoining polygon with the longer common side. Obviously, this specific operation causes the sporadic and undesired removal of some small clusters of polygons, individually with a surface lower than the minimal mapping unit but when considered altogether representing a well-defined structure, with a total area greater than the minimum mapping unit, and therefore worthy of preservation (De Marchi et al., 2007).

As a third step, this shapefile was thoroughly cleaned up by means of a vector rationalization process. Being the landform map derived by a raster, each line obtained by the raster-vector conversion reveals a jagged pattern due to the conversion of pixel boundaries into vector lines. For this reason, it was necessary to smooth out lines with the appropriate Sharc Terranova Smooth tool. This tool uses the cubic BSPLINE model to round lines and polygons, with a second degree interpolation polynomial and a medium degree of attraction to the original points (De Marchi et al., 2007).

As a fourth step, the landform map was combined, by means of the Union tool of Spatial Analyst, to the map of parent materials to create the physiographic map. The Union tool of Spatial Analyst was then used to combine the physiographic map with the land cover map to produce the first draft of the Land Unit Map, which was still lacking of soil information. This step suffered many topological problems, the most typical one consisting of the so-called "chasing lines". These lines arise from the adjacency of two or more polygons representing the same territorial entity but designed by different operators in different layers. ArcGIS works following an "All Polygons" topology, and these lines that chase intertwining create new undesired and meaningless polygons. All the undesired sliver polygons (often tiny polygons, considering their areal size, created automatically by the system by intersecting different geometric features representing the same object) were eliminated, retaining

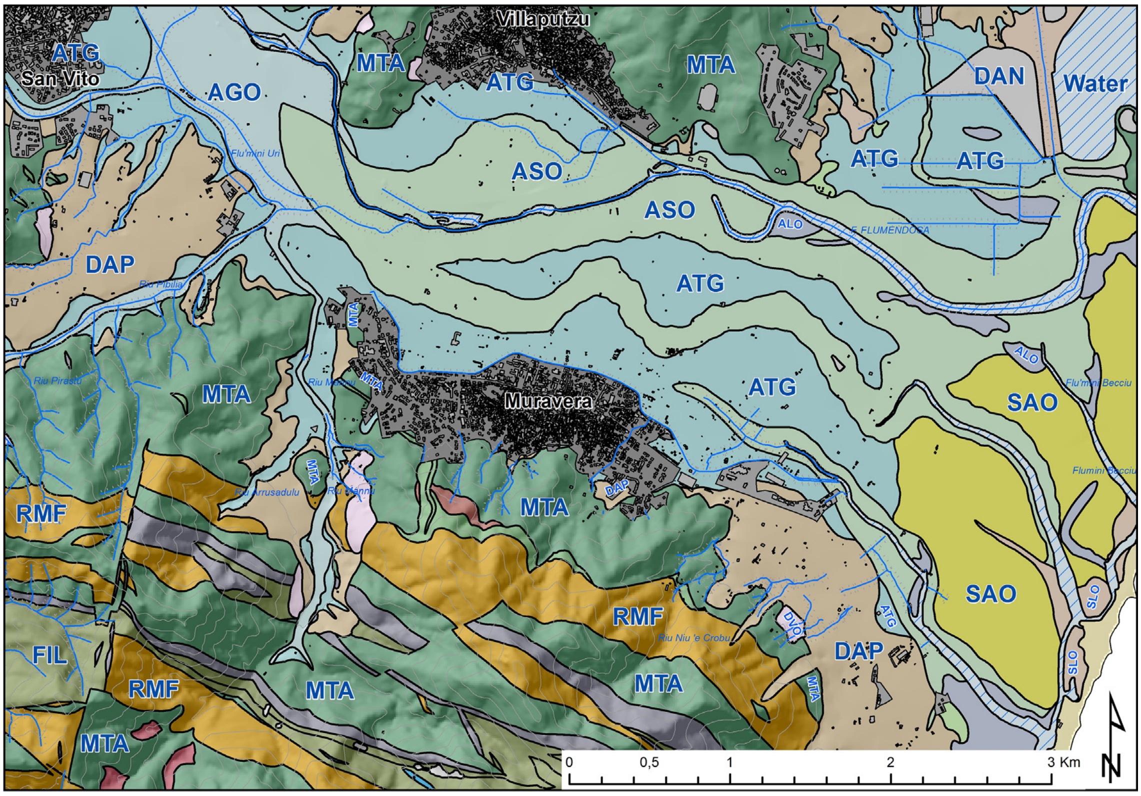

Fig. 3. Extract of the map of parent materials. Codes are those of Table 4.

the appearance and the shape of main polygons. This was achieved by calculating form analysis factors with the aim of manually identifying each feature with an overly long perimeter in relation to its area and with an overly elongated shape. An extract of the first draft of the Land Unit Map is shown in Fig. 5. Fig. 6 shows a view, from north-west, of the area shown in Figs. 2–5 and some related reference soils.

3.5. Database

A new database, the Database Soil Sardinia (DBSS), was created for this project. DBSS is a web application (http://94.92.17.59/dbss/, restricted access) set up to enter, view and export data from soil surveys. This application was created in PHP and uses a PostgreSQL database with PostGIS for geographic features. The application has many client-side interactions (Ajax) written in JavaScript. The application runs on a Linux server located at the Agenzia AGRIS Sardegna and uses Apache 2.2 as a web server. DBSS has been designed and implemented to facilitate data entry by means of a standard web browser, regardless the device used, whether tablets, smartphones or PCs, directly in the field during a survey. All the main functions are contained in a single page. It is possible to browse the detected pedons, their horizons and the related soil analysis. DBSS is integrated with GPS functionality. It is possible to provide the coordinates of a surveyed point and easily identify and extract information from several raster and vector files in the geodatabase to complete administrative data (municipality, province, region) and geographic data (elevation above sea level, slope, aspect, parent material, land cover and landform unit) about the site. These geographic utilities represent one of the added values of DBSS. To facilitate data input and data checking, some semi-automatic functionalities, such as the calculation of the available water capacity or the calculation of the soil texture class (with the kind permission of the Natural Resources Conservation Service of the United States Department of Agriculture) are included. A quality indicator has been implemented to automatically determine the completeness and accuracy of the entered data required to enable the calculation of the LCC. DBSS can export data, based on SQL queries customized by users with filters and constraints on all fields. The export produces outputs in several formats: CSV, Excel, ESRI shapefile and KLM. The database populated by DBSS was connected with ArcGIS to obtain the possibility of producing thematic maps.

The database structure for geographic features, whose spatial component has been implemented by means of the PostGIS 1.5 extension, is composed of 7 data tables that contain the descriptive

Table 5
Units of the landform map.

Class	Description
−3	Concave areas with slope >35%. Depending on lithology, it includes the concave areas of mountain slopes and upper parts of hillslopes.
−2	Concave areas with slope from 15 to 35%. Depending on lithology, it includes the concave areas of mountain middle slopes, hillslopes and upper parts of fans.
−1	Concave areas with slope from 2.5 to 15%. Depending on lithology, it includes the concave areas of lower parts of hillslopes, floodplains, fans and erosional surfaces.
0	Concave and convex areas with slope <2.5%. Depending on lithology, it includes alluvial plains, terraced surfaces, planation surfaces, morphostructural features, erosional and sedimentation plains.
+1	Convex areas with slope from 2.5 to 15%. Depending on lithology, it includes the convex areas of summit parts of ridges, fans, erosional and sedimentation surfaces located between hillslopes and plains.
+2	Convex areas with slope from 15 to 35%. Depending on lithology, it includes the convex areas of upper parts of ridges, upper parts of fans, morphostructural features.
+3	Convex areas with slope >35%. Depending on lithology, it includes the convex areas of mountain ridges and edges of morphostructural features.

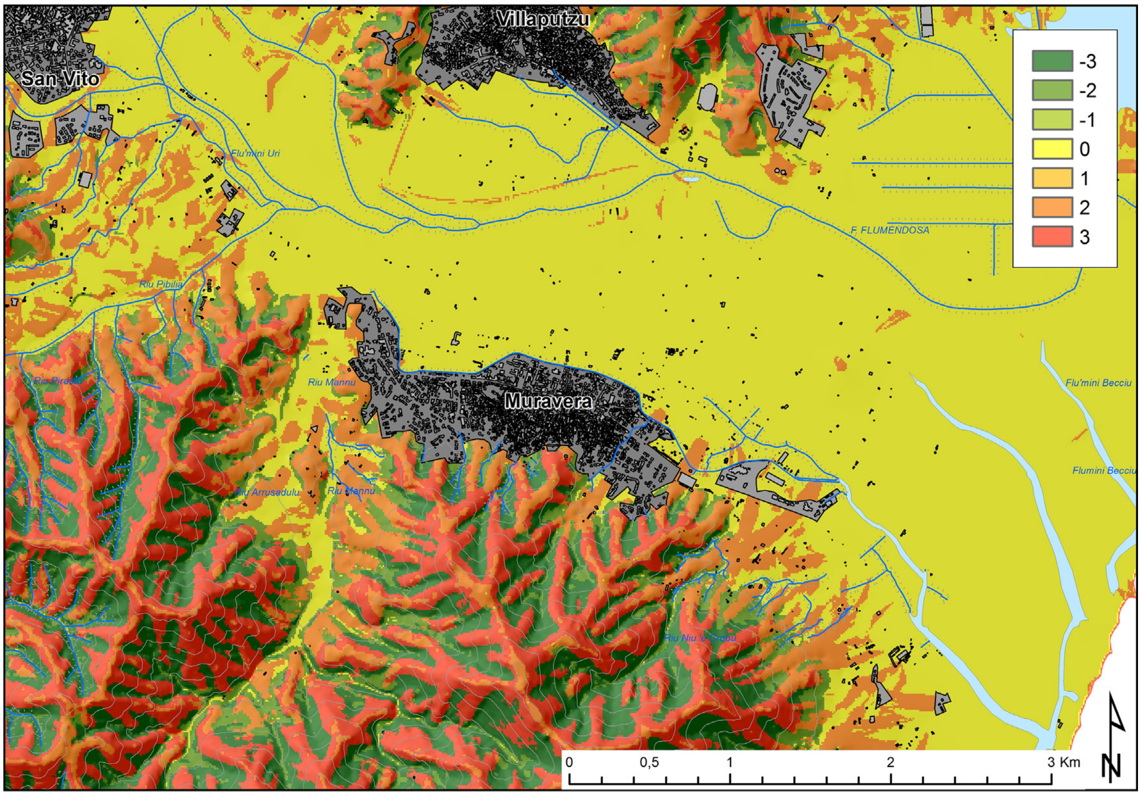

Fig. 4. Extract of the landform map. Codes are those of Table 5.

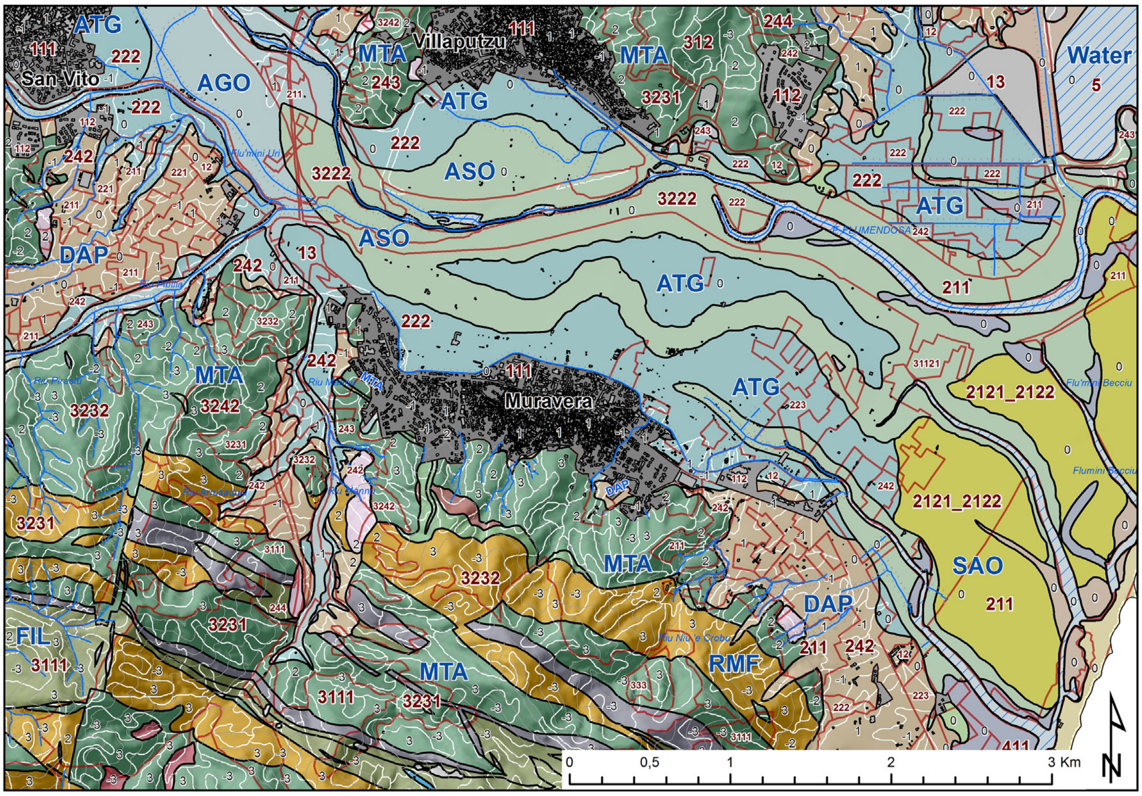

Fig. 5. Extract of the first draft of the Land Unit Map. Codes are those of Tables 3–5 (pale blue parent materials, black landform, and red land cover).

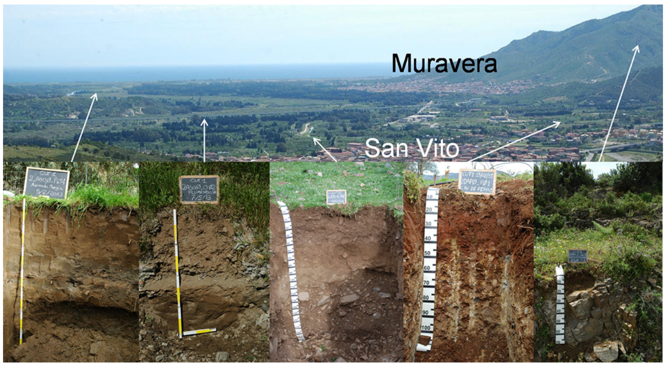

Fig. 6. View, from north-west, of the area shown in Figs. 2–5 and related reference soils.

attributes of the informative layers composing the draft of the Land Unit Map. The geodatabase runs on a server located at the Agenzia LAORE Sardegna and is connected with the DBSS running on the Linux server located at the Agenzia AGRIS Sardegna.

3.6. Validation and standardization of existing soil data

The collected existing soil data belong to soil surveys performed over a time period of almost 40 years (the oldest data date back to 1975) for different purposes and by different soil surveyors. They mostly come from unpublished studies and technical reports belonging to the partners of the project and are stored on paper.

The validation of point data (pedon data) was performed and took into consideration the following parameters: possibility for georeferentiation (presence of geographic coordinates, position on a map, land registry data), completeness and quality of site and profile description and completeness and quality of the analytical dataset. The completeness and quality of site and profile description was evaluated according to international guidelines (FAO, 2006; Schoeneberger et al., 2012), whereas that of the analytical dataset was evaluated according to national guidelines (Ministero delle Politiche Agricole e Forestali, 1998, 2000). Considering that pedon data will be used to determine soil capability classes, the minimum required data for a pedon was set as follows: i) Site description: possibility of georeferentiation and information on surface fragments, drainage and erosion; ii) Profile description: presence of horizon and layer designation and information on thickness, color, ped and void surface features, structure, consistence, concentrations, redoximorphic features, cracks and permeability class; iii) Analyses: pH, texture, exchange cations, cation exchange capacity, total nitrogen, organic carbon content, total and active $CaCO_3$. The validation process allowed classification of the pedon data as not usable, to be verified, and usable.

The long time period of soil surveying and the large number of soil surveyors involved necessitated the standardization of the terminology used in the site and profile descriptions and the standardization of the analytical methods and of the units used to express the analytical results. The terminology has been standardized according to FAO (2006) and Schoeneberger et al. (2012), whereas the analytical methods and units have been standardized according to Ministero delle Politiche Agricole e Forestali (1998, 2000).

The data of 1527 soil observations have been input so far into the DBSS, 1029 of which correspond to soil profiles.

The validation of soil maps was performed, considering the density of observations and the information given in the related legend (Soil Survey Division Staff, 1993).

4. Conclusions and future work

For the first time in Sardinia, a modern soil inventory to support land use planning is under construction using a cost-effective GIS approach and available data.

The available digital data were interpreted using consolidated and generalized knowledge regarding the influence of geology, topography and land cover on soil properties. The soil-landscape paradigm was used to predict homogeneous areas in terms of soil, geological substratum, landform and land cover. Therefore, this study's method provides a quick and robust way to allow LU identification. Digital thematic maps of soil-forming factors (parent material, landform, land cover) were produced to build the first draft of the Land Unit Map to be used as a basis for the production of the final "Land Unit and Soil capability Map of Sardinia" at a scale of 1:50,000. The dataset was developed in a GIS environment, exploiting its potential to produce derived maps by intersections, reclassifications and summarizing themes using GIS functions.

In addition to this methodology, we created a new database setup to enter, view and export data from soil surveys and a methodology for the validation and standardization of existing soil data collected over a long time period of soil surveying by a large number of soil surveyors for different purposes.

The second draft of the Land Unit Map, containing soil information, will be initially tested in 4 pilot areas. The total surface covers 184,088 ha, of which 11,319 are in the highest mountains of Sardinia, and the rest is in coastal areas. These areas have been selected on the basis of their geographic distribution (the RAS has primary interest in land planning in coastal areas) and the availability of existing soil data. The final survey density is anticipated to be 1 observation per 50 ha, i.e., a total of 3682 observations, with 5% of the observations being soil profiles.

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References

Arangino, F., Aru, A., Baldaccini, P., Vacca, S., 1986. I suoli delle aree irrigabili della Sardegna, in scala 1:100.000. Assessorato Regionale alla Programmazione Bilancio ed Assetto del Territorio, Ente Autonomo del Flumendosa, Cagliari.

Aru, A., Baldaccini, P., Delogu, G., Dessena, M.A., Madrau, S., Melis, R.T., Vacca, A., Vacca, S., 1990. Carta dei suoli della Sardegna, in scala 1:250.000. Dipartimento Scienze della Terra Università di Cagliari, AssessoratoRegionaleallaProgrammazioneBilancio ed Assetto del Territorio, SELCA, Firenze.

Aru, A., Tomasi, D., Vacca, A., 2006. Aspects of environmental degradation in Sardinia. In: Tennyson, L., Zingari, P.C. (Eds.), Proceedings of the International Conference "Preparing for the Next Generation of Watershed Management Programmes and Projects: Water Resources for the Future", Porto Cervo, Sassari, Sardinia, Italy, 22–24 October 2003. FAO, Rome, pp. 163–178. Watershed Management and Sustainable Mountain Development Working Paper 9.

Bastian, O., 2000. Landscape classification in Saxony (Germany) – a tool for holistic regional planning. Lands. Urban Plann. 50, 145–155.

Behrens, T., Schmidt, K., Scholten, T., 2008. An approach to removing uncertainties in nominal environmental covariates and soil class maps. In: Hartemink, A.E., McBratney, A., Mendonça-Santos, M.L. (Eds.), Digital Soil Mapping with Limited Data. Springer, pp. 213–224.

Birkeland, P.W., 1999. Soils and Geomorphology, third ed. Oxford University Press, New York.

Blum, W.E.H., 2008. Characterisation of soil degradation risk: an overview. JRC Scientific and Technical Reports – EUR 23438 EN, JRC 46574. In: Tóth, G., Montanarella, L., Rusco, E. (Eds.), Threats to Soil Quality in Europe. JRC, Ispra, pp. 5–10.

Brady, N.C., Weil, R.R., 2008. The Nature and Properties of Soils, fourteenth ed. Prentice Hall/Pearson Education, Upper Saddle River, New Jersey.

Buol, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2011. Soil Genesis and Classification, sixth ed. John Wiley, Chichester, UK.

Carboni, S., Palomba, M., Vacca, A., Carboni, G., 2006. Paleosols provide sedimentation, relative age, and climatic information about the alluvial fan of the River Tirso (Central-Western Sardinia, Italy). Quater. Int. 156–157, 79–96.

Costantini, E.A.C., 2009. The land capability classification. In: Costantini, E.A.C. (Ed.), Manual of Methods for Soil and Land Evaluation. Science Publishers, Enfield, NH, pp. 37–46.

De Marchi, D., Maffei, S., Ciccarelli, L., Bellancini, A., Guidi, D., 2007. ShArc 4.2 Manuale di riferimento. Terra Nova Sistemi Informativi Territoriali, Urbania.

FAO, 2006. Guidelines for Soil Description, fourth ed. FAO, Rome.

Gorini, M.A.V., 2009. Physiographic classification of the ocean floor: a multi-scale Geomorphometric approach. In: Purves, R., Gruber, S., Straumann, R. (Eds.), Proceedings of Geomorphometry 2009, Zurich, Switzerland, 31 August – 2 September 2009. University of Zurich, Zurich, pp. 98–105.

Harris, T.M., Elmes, G.A., 1993. The application of GIS in urban and regional planning: a review of the North American experience. Appl. Geogr. 13, 9–27.

Hudson, B.D., 1992. The soil survey as a paradigm-based science. Soil Sci. Soc. Am. J. 56, 836–841.

IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006, First Update 2007. World Soil Resources Reports No. 103. FAO, Rome.

Iwahashi, J., Pike, R.J., 2007. Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature. Geomorphology 86, 409–440.

Jacobs, H.M., 2000. Practicing land consolidation in a changing world of land use planning. Kart og Plan 60, 175–182.

Jenny, H., 1941. Factors of Soil Formation. A System of Quantitative Pedology. McGraw Hill Book Company, New York, NY.

Khresat, S., Al-Bakri, J., Al-Tahhan, R., 2008. Impacts of land use/cover change on soil properties in the Mediterranean region of northwestern Jordan. Land Degrad. Develop. 19 (4), 397–407.

Klingebiel, A.A., Montgomery, P.H., 1961. Land Capability Classification. In: Agriculture Handbook No. 210, Washington, D.C.

Kocygit, R., Demirci, S., 2012. Long-term changes of aggregate-associated and labile soil organic carbon and nitrogen after conversion from forest to grassland and cropland in northern Turkey. Land Degrad. Develop. 23 (5), 475–482.

Lisio, A., Russo, F., 2010. Thematic maps for land-use planning and policy decisions in the Calaggio stream catchment area. J. Maps 6 (1), 68–83.

MacMilland, R.A., Shary, P.A., 2009. Landforms and landform elements in geomorphometry. In: Hengl, T., Reuter, H.I. (Eds.), Geomorphometry: Concepts, Software, Applications. Develop. Soil Sci. 33, 227–254.

Madrau, S., Deroma, M., Loj, G., Baldaccini, P., 2006. Carta Ecopedologica della Sardegna, in Scala 1:250.000. Dipartimento di Ingegneria del Territorio, Università degli Studi di Sassari, Sassari.

Mairota, P., Thornes, J.B., Geeson, N.A., 1997. Atlas of Mediterranean Environments in Europe: the Desertification Context. John Wiley & Sons Ltd, Chichester, England.

Marrone, V.A., Vacca, A., Vecchio, G., Apollaro, C., Caruso, A.M., Scarciglia, F., Aru, A., De Rosa, R., 2008. Pedopaesaggi e suoli del foglio IGMI 549-Muravera (Sardegna sud-orientale). In: Ottonello, G. (Ed.), GEOBASI – Il Foglio IGMI N° 549-Muravera. PaciniEditore, Pisa, pp. 59–85.

Miall, A.D., 1997. The Geology of Stratigraphic Sequences. Springer-Verlag, New York.

Ministero delle Politiche Agricole e Forestali, 1998. Metodi di analisi fisica del suolo. In: Collana di metodi analitici per l'agricoltura. Franco Angeli Editore, Milano, Italia.

Ministero delle Politiche Agricole e Forestali, 2000. Metodi di analisi chimica del suolo. In: Collana di metodi analitici per l'agricoltura. Franco Angeli Editore, Milano, Italia.

Muñoz-Rojas, M., Jordán, A., Zavala, L.M., De la Rosa, D., Abd-elmabod, S.K., Anaya-Romero, M., 2012. Impact of land use and land cover changes on organic carbon stocks in Mediterranean soils (1956–2007). Land Degrad. Develop.. http://dx.doi.org/10.1002/ldr.2194 (in press) http://onlinelibrary.wiley.com/doi/10.1002/ldr.2194/pdf.

Nour, A.M., 2011. The potential of GIS tools in strategic urban planning processes; as an approach for sustainable development in Egypt. J. Sustain. Develop. 4 (1), 284–298.

Papadimitriou, F., 2012. Modelling landscape complexity for land use management in Rio de Janeiro, Brazil. Land Use Policy 29, 855–861.

Prothero, D.R., 1990. Interpreting the Stratigraphic Record. W.H. Freeman & Company, New York.

Regione Autonoma della Sardegna, 2006. Piano Paesaggistico Regionale: Norme Tecniche di Attuazione – Allegati. Settembre 2006, Available on the Internet at: http://www.sardegnaterritorio.it/documenti/6_83_20060907193936.pdf (accessed 18.09.13.).

Regione Autonoma della Sardegna, 2008. Piano Paesaggistico Regionale: Linee Guida per l'adeguamento dei Piani Urbanistici Comunali al PPR e al PAI. In: Prima Fase – Il Riordino delle Conoscenze. Assetto Ambientale. Luglio 2008, Available on the Internet at: http://www.sardegnaterritorio.it/documenti/6_83_20081007095546.zip (accessed 18.09.13.).

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survey Staff, 2012. Field Book for Describing and Sampling Soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Shary, P.A., Sharaya, L.S., Mitusov, A.V., 2002. Fundamental quantitative methods of land surface analysis. Geoderma 107, 1–32.

Sierra, M., Martínez, F.J., Sierra, C., Aguila, J., 2009. Correlations between pedological parameters in relation to lithology and soil type in Almería (SE Spain). J. Arid Environ. 73 (4–5), 493–498.

Soil Survey Division Staff, 1993. Soil Survey Manual. In: USDA-NRCS Agricultural Handbook No. 18. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, eleventh ed. USDA-Natural Resources Conservation Service, Washington, DC.

Solon, J., Roo-Zielińska, E., Degórski, M., 2012. Landscape scale of topography-soil-vegetation relationship: influence of land use and land form. Polish J. Ecol. 60 (1), 3–17.

Vacca, A., 1996. Stato della cartografia e dell'informazione pedologica in Sardegna. In: Atti del Convegno "L'informazione pedologica nella prospettiva di un Servizio Regionale del Suolo", E.R.S.A.L., Regione Lombardia, 26–27 ottobre 1994, Milano, pp. 187–190.

Vacca, A., 2000. Effect of land use on forest floor and soil of a *Quercus suber* L. forest in Gallura (Sardinia, Italy). Land Degrad. Develop. 11 (2), 167–180.

Vacca, A., Vacca, S., 2001. Soil degradation in Sardinia – Historical causes and current processes due to anthropogenic pressure. Petermanns Geograph. Mitteilung. 145 (4), 68–83.

Vacca, A., Loddo, S., Serra, G., Aru, A., 2002. Soil degradation in Sardinia (Italy): main factors and processes. In: Zdruli, P., Steduto, P., Kapur, S. (Eds.), 7th International Meeting on Soils with Mediterranean Type of Climate (Selected Papers), Options Méditerranéennes, Series: Mediterranean Seminars, vol. A50, pp. 413–423. Valenzano (BA).

Wondie, M., Teketay, D., Melesse, A.M., Schneider, W., 2012. Relationship between topographic variables and land cover in the Simen Mountains National Park, a World Heritage Site in Northern Ethiopia. Int. J. Remote Sens. Appl. 2 (2), 36–43.

Zevenbergen, L.W., Thorne, C.R., 1987. Quantitative analysis of the land surface topography. Earth Surf. Process. Landf. 12, 47–56.

Zonneveld, I.S., 1989. The land unit – a fundamental concept in landscape ecology, and its applications. Lands. Ecol. 3, 67–86.

Zoppi, C., Lai, S., 2010. Assessment of the regional landscape plan of Sardinia (Italy): A participatory-action-research case study type. Land Use Policy 27, 690–705.

Zoppi, C., Lai, S., 2013. Differentials in the regional operational program expenditure for public services and infrastructure in the coastal cities of Sardinia (Italy) analyzed in the ruling context of the Regional Landscape Plan. Land Use Policy 30, 286–304.

Şahin, Ş., Bekişoglu, Ü., 2009. Landscape planning and management strategies for the Zir Valley, near Ankara, Turkey. Environ. Geol. 57, 52–62.