Taylor & Francis
Taylor & Francis Group

Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

Soil rooting depth of Italy

Rosa Rivieccio, Claudia Di Bene, Massimo Paolanti, Marco Marchetti & Rosario Napoli

JOURNAL OF MAPS
2019, VOL. 16, NO. 2, 36–42
https://doi.org/10.1080/17445647.2019.1690595

Science

OPEN ACCESS Check for updates

Soil rooting depth of Italy

Rosa Rivieccio [a,b], Claudia Di Bene [a], Massimo Paolanti[c], Marco Marchetti [b] and Rosario Napoli [a]

[a]Research Centre for Agriculture and Environment, Council for Agricultural Research and Economics (CREA-AA), Rome, Italy; [b]Department of Biosciences and Territory (DiBT), University of Molise, Isernia, Pesche, Italy; [c]Pedologist freelance, Rome, Italy

ABSTRACT
Soils perform several functions in delivering ecosystem services and soil thematic maps are useful for environmental modelling, landscape planning, and management optimization. This study aimed at producing the first soil rooting depth map of Italy at 1:250,000 scale based on the legacy soil maps, soil data and benchmark profiles, combined with the auxiliary data. The map highlights that moderately deep (33%) and deep (25%) soils are predominant and mainly distributed in hilly areas, while very deep soils (18%) are prevalent in the fluvial and coastal plains. The validation procedure showed that 87% of the soil rooting depth map classes fall within the same and adjacent classes of the measured soil profiles database. The soil rooting depth map of Italy at 1:250,000 scale can be a useful tool to support land management and spatial planning in terms of agro-environmental measures, making reliable assessments for ecological sustainability studies, and for environmental territorial analyses.

ARTICLE HISTORY
Received 9 November 2018
Revised 30 October 2019
Accepted 5 November 2019

KEYWORDS
Soil mapping; soil subsystem; rooting depth map; Italy

1. Introduction

Soils play a fundamental role in protecting, restoring and promoting sustainable use of terrestrial ecosystems (Arnold, Szabolcs, & Tasgulian, 1990). They perform many functions in delivery of ecosystem goods and services (Bouma, 2010; Dominati, Mackay, Green, & Patterson, 2014) such as food production and biomass, water and nutrient cycle, climate regulation, energy provision, and biodiversity (Benedetti, Dell'Abate, & Napoli, 2013; MEA, 2005). The number of scientific publications stressing on the importance of soil functions in ecosystem services is increasingly growing (Haygarth & Ritz, 2009; Grêt-Regamey, Weibel, Kienast, Rabe, & Zulian, 2015; Greiner et al., 2017). Mainstreaming ecosystem services and soil functions into policies planning and decision-making (Grêt-Regamey, Weibel, Kienast, Rabe, & Zulian, 2015) is important for supporting the sustainable use of soil resources (Bouwma, Schleyer, Primmer, Winkler, & Bezák, 2018; van der Biest et al., 2013) at global, national, regional and local scales.

In this context, soil mapping is essential to understand how soils contribute to human well-being and to support policies which have an impact on natural resources. Traditionally, soil mapping is achieved through a soil survey inventory carried out by experts who understand interactions between soil-forming factors (Lagacherie, McBratney, & Voltz, 2007) and represents a discrete model of spatial variation (Kempen, Brus, Stoorvogel, Heuvelink, & de Vries, 2012). Thus, it extended relationships directly observed at limited locations, with relatively few samples, to produce useful soil maps at the landscape scale (Miller, 2017), by simply applying the principle of spatial association (Hole & Campbell, 1985). In the last decades, local knowledge, data availability, and the use of database have increased exponentially, improving the quality of the maps produced (Miller, 2017). More recently, alternative approach as the Digital Soil Mapping techniques (e.g. regression kriging and machine-learning) employ geographical information systems to analyse and combine environmental covariates with observed points to improve maps quality (Hengl et al., 2015; McBratney, Mendonca Santos, & Minasny, 2003), and require digital data sources as input variables for the quantitative models, well distributed over geographic- and feature space (Leenaars et al., 2018). Nevertheless, at wide scales traditional soil maps are still widely used in areas where great diversity of climate, geology, landscapes, and soil-forming processes exists, or where limited and not homogeneously distributed soil observations are available. In these situations, Digital Soil Mapping techniques – mainly based on the correlation among land covariates and soil properties – may not produce satisfactory results.

Soil maps and derived thematic maps efficiently communicate complex spatial information and constitute a very important tool for environmental modelling, landscape planning, and management

CONTACT Rosa Rivieccio rosa.rivieccio@unimol.it, rosam.rivieccio@gmail.com, rosa.rivieccio@crea.gov.it
Supplemental data for this article can be accessed at https://doi.org/10.1080/17445647.2019.1690595

optimization (Miller, 2017; Pereira, Brevik, Muñoz-Rojas, & Miller, 2017). Particularly, thematic soil maps show the distribution of soil property and quality connected with a specific area. Among soil quality maps, the rooting depth map is one of the most important because it represents the volume of soil potentially explorable by plant's roots to effectively extract water and nutrients for growth (Arrouays, McKenzie, Hempel, Richer de Forges, & McBratney, 2014; Global Soil Map, 2015).

In 1997, the Terrestrial Observation Panel for Climate of the Global Climate Observation System identified the 95% rooting depth as a key variable needed to quantify the interactions among climate, soil, and plants features. Vertical root distributions significantly influence soil productivity through the water, carbon, and nutrients fluxes as well as the distribution and activities of soil fauna. Roots transport nutrients and water upwards, but they are also pathways for carbon and nutrient transport into deeper soil layers and for deep water infiltration (Jarvis, 2011) and affect the weathering rates of soil minerals (Yang, Donohue, & McVicar, 2016). Generally, when no root-restricting zone is identified, a depth of 150 cm can be used to approximate the root zone depth (Dobos, Sinclair, & Robotham, 2012). Conversely, when limiting factors exist the rooting depth can be shorter than the entire soil profile. The main limiting factors influencing rooting depth are: underlying rocks, coarse fragments content exceeding 80% of the penetrable volume (e.g. hardpan and plowpan), abruptness of textural change over depth, horizon compaction and cementation, pH extremely acidic and or alkaline, and other physical and chemical properties (FAO, 2006; Leenaars et al., 2018).

Despite the importance of rooting depth in the control of terrestrial hydrological and biogeochemical processes, its distribution and its relationships with plant physiology and pedo-climatic characteristics remain largely unknown. This is mainly due to the difficulties in the direct quantification of rooting depth using field approaches. To overcome the lack of direct observations, several combined approaches, based on modelling, use of primary soil profile data, and various scientific hypotheses, have been proposed to estimate the soil rooting depth (Leenaars et al., 2018; Wang-Erlandsson et al., 2016). For instance, Musters and Bouten (1999) used inverse model to indirectly estimate rooting depths in a forested stand by quantifying spatial variability in soil water dynamics, while Schenk and Jackson (2002a, 2002b) and Zeng (2001) assembled observations of root profiles from the literature to yield a global dataset of root biomass with depth for different biomes in order to construct maps of global ecosystem rooting depths (Schenk & Jackson, 2009).

This study aimed at producing the first unified soil rooting depth map of the whole Italian territory at 1:250,000 scale based on the based on the legacy soil maps, soil data and benchmark profiles available at regional administrative scales, combined with the auxiliary data to further fill the gaps in areas without soil data.

2. Materials and methods

2.1. Study area

The study area covers the whole Italian territory (20 administrative Regions plus South Tyrol as autonomous province), sizing about 302,073 km^2 and ranging from sea level to 4810 m a.s.l. (Mont Blanc in Aosta Valley Alps, the highest elevation of geographic Europe). A remarkable morphological variability of the Italian territory is reflected by its geologically young land, with great variety of lithological composition and landscapes. Orography is mainly characterized by hilly areas (42%), followed by mountains (35%) and plains (23%). As reported by Costantini et al. (2013), all these factors affect the pedodiversity of Italy.

Italian climates are strongly influenced by both orography (mainly Alps and Appennines rough morphology) and Mediterranean Sea (important reservoir of heat and humidity for the inland). On average, the long-term mean annual air temperature is 12.6°C (ranging from 8.7°C to 16.5°C), while the cumulated mean annual rainfall is 785 mm (https://www.reterurale.it/agroclima).

In terms of land cover, Italy is mainly characterized by agricultural lands (about 51%) and woodlands and semi-natural environments (about 41%), whilst artificial surfaces do represent only 5% of total surface area, with a very irregular distribution over the national territory due to the orographic features and the different level of urbanization (ISPRA, 2012; Marras et al., 2018). More details on the most widespread land uses are given by Costantini and Dazzi (2013).

2.2. Data Sources

To date, in Italy the highest detail soil map of major soils distribution at national coverage is available at 1:1,000,000 scale (Costantini et al., 2012; Filippi, 2005). This resolution is not good enough for a detailed model assessment. Thus, in 1999 the Italian Ministry of Agricultural, Food and Forestry Policies funded the national systematic soil survey programme to construct a soil map of Italy at 1:250,000. At present, several administrative regions have produced pedological data as maps, catalogues, atlases, and database using this scale (Costantini et al., 2014), but the whole national territory is not yet covered at this scale. Therefore, in the present study, soil data observation points and pedological maps at 1:250,000 scales were used as main data sources to produce the first soil rooting depth map of Italy at this scale. Soil data observation points refer to all georeferenced soil profiles (24,502) database available at CREA – Research Centre for Agriculture and Environment, while pedological maps to all maps, both in digital- and in paper-based format, available at CREA – Research Centre for Agriculture and Environment or collected from administrative regions (see Table S1 for list and references).

The auxiliary data used were:

- Digital Elevation Model (DEM; ASTER GDEM) of Italy with a 30 m resolution cell, used to derive slope raster (Zevenbergen & Thorne, 1987), reclassified in classes according to Field Soil Survey and Data Entry Manual (Costantini, 2007).
- Geological maps of Italy at 1:100,000 (http://www.isprambiente.gov.it/it/cartografia/carte-geologiche-e-geotematiche/carta-geologica-alla-scala-1-a-100000) and 1:50,000 scales (http://www.isprambiente.gov.it/it/cartografia/carte-geologiche-e-geotematiche/carta-geologica-alla-scala-1-a-50000), used to derive the parent material maps.
- CORINE land cover (CLC) map of Italy 2012 (http://www.sinanet.isprambiente.it/it/sia-ispra/download-mais/corine-land-cover/), used to support video-photointepretation to distinguish different cartographic units (CU) by land use, typical climate and parent material association.
- Bioclimatic map (http://www.soilmaps.it/download/csi-BrochureSR_a4.pdf), used to support video-photointepretation to distinguish different CU by bioclimatic regions.

If soil maps at 1:250,000 scale missed (e.g. Molise, Umbria, Liguria, Aosta Valley, and South Tyrol) – or were incomplete (e.g. Friuli Venezia Giulia and Umbria), the following maps at different scale were used (see Table S1 for list and references):

- Pedological maps at higher scale than 1:250,000 (mainly 1:25,000 and 1:50,000; Table S1).
- Soil Italian map at 1:1,000,000 scale (Costantini et al., 2012).
- Soil Regions of Italy at 1:5,000,000 scale (http://www.soilmaps.it/download/csi-BrochureSR_a4.pdf), used to support traditional video-photointepretation to distinguish different CU, characterized by typical climate and parent material association, by soil cover.
- Eco-pedological map at 1:250,000 scale by European Soil Bureau on behalf of Italian Ministry of Environment, between 1998 and 2001 (European Commission, 1998; Filippi, 2005).
- Atlas of areas at risk of desertification (Costantini et al., 2009; Costantini, Urbano, Bonati, Nino, & Fais, 2007).

2.3. Data processing

The soil rooting depth map of Italy at 1:250,000 scale was processed and edited using ESRI ArcGIS 9.2, using to the Universal Transverse Mercator WGS84 fuse 32 (EPSG 32632). Data processing followed five steps:

1. Digitalization of all the paper-based maps in vector layers.
2. Building the soil subsystem vectorial layer at 1:250,000 scale for the regional areas where soil maps missed or were incomplete. This was performed using an *ad hoc* traditional video-photointerpretation of the landscape in a GIS environment, by combining the existing soil maps at more detailed scales (Table S1) with the above-mentioned auxiliary data (i.e. DEM, CORINE land cover, geological and pedological maps).
3. Import all regional soil subsystem vectorial layers and soil data profile in a geodatabase.
4. Geographic union of all regional layers in one soil subsystem national layer, and geographic harmonization at administrative boundaries with auxiliary data.
5. Characterization of the soil subsystem layer of each CU at geographic level, using the most representative and frequent soil type.

At this purpose, an integrated approach was used to link soil CU (3260) to the representative soil profile properties and qualities (Table 1). Depending on the available data and information, the following approaches were chosen: (i) if soil typological units were available (e.g. Abruzzo, Lazio, Tuscany, and Apulia), we selected the most frequent one and its benchmark profile; (ii) if soil typological units were unavailable (e.g. Campania, Emilia Romagna, Marche, Molise, Sardinia, Sicily, Umbria, Veneto), we selected the representative profile of the most frequent land component inside the CU, by choosing the best soil observation correlated with the specific combination of morphological class, lithology, and land cover (Costantini et al., 2014; (iii) if neither the soil typological units nor the soil profile were available, we used general information reported in soil system map (e.g. Aosta Valley and Liguria) to derive a soil type dataset as dominant.

Table 1 shows the summary of the work done to fill the gaps both for geographic level, by harmonizing the available soilscapes maps and eventually building news, and for soil information gathering and processing, as results of the three above-mentioned approaches.

Since in some soil regional layers the no-soil areas were lacking or not updated, a further harmonization procedure was necessary according to the following CLC classes:

Table 1. Summary data used to evaluate the final soil rooting depth map for each Italian administrative region with the corresponding area.

	Geographic layer				Soil profiles and minipits data			
Regions	250K (%)	<250K (%)	>250K (%)	CU (*n*)	STU (*n*)	LC (*n*)	ST (*n*)	Area (km^2)
Abruzzo	yes	0	0	104	104			10,856
Aosta Valley	n.a.	0	100	18		5	13	3269
Apulia	yes	0	0	213	213			19,586
Basilicata	yes	0	0	75	75			10,097
Calabria	yes	0	0	156	156			15,260
Campania	yes	0	0	223	80	143		13,703
Emilia Romagna	yes	0	0	148	148			22,240
Friuli Venezia Giulia	n.a.	85	15	52			52	7879
Lazio	yes	0	0	185	185			17,270
Liguria	n.a.	0	100	55		55		5420
Lombardy	yes	0	0	64	34		30	23,921
Marche	yes	0	0	113		113		9756
Molise	n.a.	25	75	197		197		4472
Piedmont	yes	0	0	432	115	2	315	25,451
Sardinia	yes	0	0	33		33		24,146
Sicily	yes	0	0	538		538		25,895
South Tyrol (Alto Adige)	n.a.	0	100	13			13	7416
Trentino	yes	0	0	148		148		6218
Tuscany	yes	0	0	151	151			23,043
Umbria	n.a.	50	50	131		131		8482
Veneto	yes	0	0	211		3	208	18,469
Total				*3260*	*1261*	*1368*	*631*	*302,073*

Geographic layer columns: 250K – Presence or not of the soil subsystem maps, <250K (%) – Achieved from existing more detailed soil maps, new 250K (%) – Built as new, CU (n) – Total number of final harmonized Cartographic Units. Soil profiles and minipits data columns: Number of soil dataset retrieved from Soil Typological Unit (STU), correlated with most representative Land Component (LC), and recovered from soil map at smallest scales (Soil System Level – ST).

- *Artificial areas*: Codes 1.1 and 1.2 (urban areas).
- *Uncovered areas*: Codes 1.3 (mine, dump and construction site) and 3.3 (beaches, dunes, sands, bare rocks, sparsely vegetated areas, and glaciers and perpetual snow)
- *Wetlands and water bodies*: Codes 4.1 (inland wetlands), 4.2 (maritime wetlands), 5.1 (inland waters), and 5.2 (marine waters).

Finally, the Soil Rooting Depth map was derived, adopting the official USDA root-restricting depth classification (Soil Survey Manual, 2017):

- Class 1: Very shallow (less than 25 cm depth)
- Class 2: Shallow (between 25 to less 50 cm depth)
- Class 3: Moderately deep (50 to less than 100 cm depth)
- Class 4: Deep (100 to less than 150 cm depth)
- Class 5: Very deep (over 150 cm depth)

The attribute of each rooting depth class was reported in each CU.

Figure 1 shows the flow chart of the processing procedures used to build the soil rooting depth map of Italy at 1:250,000 scale.

A validation process was applied to compare the rooting depth classes derived with the measured rooting depth of soil profiles for the whole Italian territory. Among all CU (3289), 1150 were excluded because there were neither soil profiles (1121) nor soil areas (29). Thus, for the validation process we selected the 2168 CU (66% of the total CU) where soil profiles data (24,502) were provided. More details are reported in Table 2.

3. Results and discussion

In this work, for the first time, we produced the first unified soil rooting depth map for the whole of Italy at 1:250,000 scale (Main Map). To this aim – in a GIS environment – we processed the soil subsystem layer using an integrated approach based on the available legacy soil maps, soil data, soil profiles, and auxiliary data, filling the gaps in the no covered areas.

The soil subsystem layer – used to derive the soil rooting depth map – is composed by 3289 CU, 30,045 polygons, and 24,502 observation sites with analysis (profiles) widespread in all national territory (302,084 km^2). This soil layer greatly increases the detail of soil map in Italy (from 1:1,000,000–1:250,000 scale).

The soil rooting depth map shows that 1% of the total area is classified as uncovered areas, urban areas, and wetlands and water bodies (CLC, 2012), while the 99% (287,368 km^2) is soil area, split in five rooting depth classes: Very shallow (class 1), shallow (class 2), moderately deep (class 3), deep (class 4), and very deep (class 5), according to USDA classification (Soil Survey Manual, 2017).

At the national level, the soil area falling in the moderately deep class is predominant (33%), followed by deep (25%), and very deep classes (18%). The soil areas covered by very shallow and shallow rooting depth counts together for 24% (Main Map). This map highlights that 3–5 classes (from moderately deep to very deep) are mainly distributed in coastal, fluvial and hilly areas, while 1–2 classes are scattered in mountain chain areas (Appenine and Alps). The

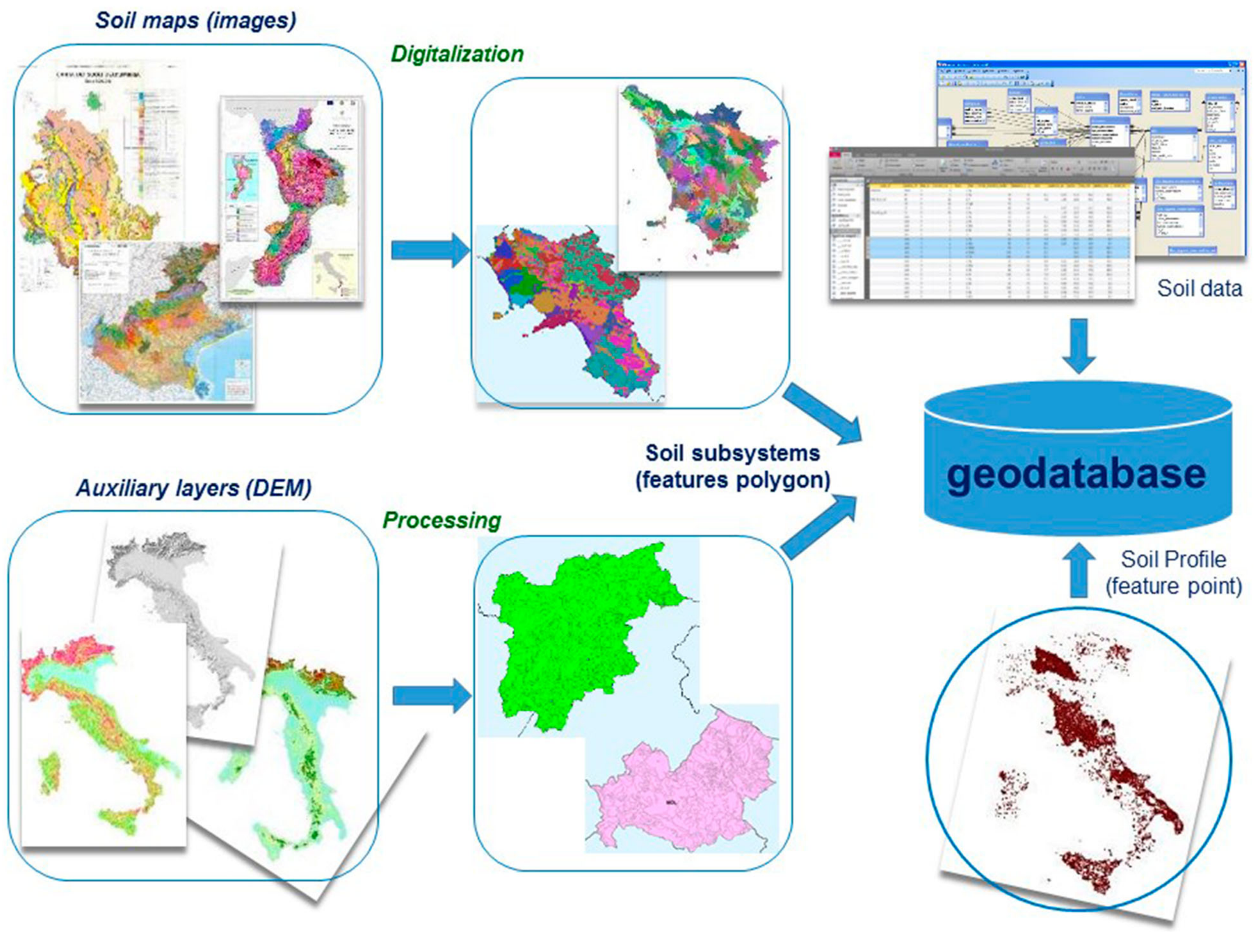

Figure 1. Flow chart of the processing procedures used to build the soil rooting depth map of Italy at 1:250,000 scale. Conversion of all map images in vectorial layers, processing of regional map gaps, import in a geodatabase all regional layers of soil data (maps and profiles).

Table 2. Type, number of cartographic units, polygons, and soil profiles, and surface for the whole of Italy.

Type	CU (n)	Polygons (n)	Soil profile (n)	Surface (km^2)
No soil areas	29	4980	–	4,076
No soil profiles	1,121	1906	–	45,596
Area covered by soil profiles	2168	25,144	24,502	252,400
Total	*3289*	*30,045*	*25,402*	*302,073*

Table 3. Matching of rooting depth classes (1–5) between soil rooting depth map at 1:250,00 scale and soil profiles data for whole of Italy, number of cartographic units (CU), polygons, and soil profiles, and surface area covered.

Matching of rooting depth class	CU (n)	Polygons (n)	Soil profile (n)	Surface (km^2)
Complete equivalence	836	10,805	10,109	107,938
Adjacent class	991	11,089	11,005	112,116
No adjacent class	341	3250	3388	32,346
Total	*2168*	*25,144*	*25,402*	*252,400*

soil rooting depth distribution confirms the high environments and soilscapes variability of the whole territory. However, the spatialization of rooting depth was less reliable at administrative boundary level of Liguria, Aosta Valley, and South Tyrol regions, where soil profiles are lacking (Table 1).

On average, the number of soil profiles per CU is 11, ranging from 1 (366 records, over an area of 17,656 km^2) to 395 (1 record, over an area of 1356 km^2). The weighted average of number of soil profiles per surface unit area (km^2) is 0.24 with a standard error of 0.02. For the validation procedure, we compared the soil rooting depth map with the measured rooting depth of soil profiles. As reported in Table 3, the 41% of soil profiles showed an equivalence of soil rooting depth with the map. This equivalence covers 43% of polygons, 39% of CU, and 43% of surface area. Similar percentage of coverage was observed for adjacent classes (Table 3). The complete class equivalence together with the adjacent class covered the 87% of the surface area. The validation showed that only 14% of soil rooting depth profile classes were not equivalent with the classes reported on the map. Adjacent classes were considered in a good way in the validation process because soil rooting depth is normally considered as a 'functional' soil characteristic, that is not concurring to define directly the membership to different Soil Typological Unit (STU). As important consequence the STU groups similar soils that could have functional characteristics straddling different adjacent classes (i.e. rooting depth from shallow to very shallow).

4. Conclusions

The soil subsystem layer at 1:250,000 allows a better previsions of the soil pedological characteristics and qualities, improving the environmental planning for future ecological sustainability studies. In fact, the soil rooting depth map at 1:250,000 scale for the whole of Italy is of crucial importance for land policies because it can be a useful tool to support land management and spatial planning in terms of agro-environmental measures, and to make reliable assessments for ecological sustainability studies, and for environmental territorial analyses (e.g. regulation services).

For instance, this map can be combined with the drainage class layers and soil texture to extract the potential water storage, useful to produce the available water capacity of the soil profile.

Finally, even though approximate, the soil rooting depth map – produced in this study – is easy to understand and rapid to produce using GIS tool to store, retrieve and manipulate the huge amount of data needed to compute and map soil properties and quality by intersections, reclassifications, and summarizing operations on attribute data.

Software

The soil rooting depth map was imported, processed (unioned and dissolved), and edited using Esri ArcGIS 9.2. The soil rooting depth map projection was the Universal Transverse Mercator WGS84 fuse 32 (EPSG 32632).

Acknowledgements

The authors wish to thank all regional administrations for providing soil data and layer information, and the Regional Agency for Extension Services of Latium (ARSIAL) which financed the Soil Latium Region (SOILRELA) project. We further acknowledge CREA-AA in Rome for technical support and for providing the Latium soil map. R. Riviecciowas funded by a University of Molise PhD studentship (2015–2018).

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Rosa Riviecciio http://orcid.org/0000-0001-9749-8500
Claudia Di Bene http://orcid.org/0000-0002-3830-251X
Marco Marchetti http://orcid.org/0000-0002-5275-5769
Rosario Napoli http://orcid.org/0000-0002-2780-8734

References

Arnold, R. W., Szabolcs, I., & Tasgulian, V. O. (1990). *Global soil change report of an IIASA-ISSS-UNEP Task Force on the role of soil in global change*. Laxenburg, Austria: International Institute for Applied Systems Analysis, 110 pp.

Arrouays, D., McKenzie, N., Hempel, J., Richer de Forges, A. C., & McBratney, A. B. (2014). *Global soil map: Basis of the global spatial soil information system*, pp. 494. Leiden: CRC Press/Balkema.

Benedetti, A., Dell'Abate, M. T., & Napoli, R. (2013). Soil functions and ecological services. In E. A. C. Costantini & C. Dazzi (Eds.), *The soils of Italy, world soils book series*. New York, NY: Springer. doi:10.1007/978-94-007-5642-7_7.

Bouma, J. (2010). Implications of the knowledge paradox for soil science. *Advanced in Agronomy*, *106*, 143–171. doi:10.1016/S0065-2113(10)06004-9

Bouwma, I., Schleyer, C., Primmer, E., Winkler, K. K., & Bezák, P. (2018). Adoption of the ecosystem services concept in EU policies. *Ecosystem Services*, *29*, 213–222. doi:10.1016/j.ecoser.2017.02.014

Costantini, E. A. C. (2007). *Linee guida dei metodi di rilevamento e informatizzazione dei dati pedologici*. Firenze, Italia: CRA_ABP, pp. 296 (in Italian, with English abstract). Retrieved from http://www.soilmaps.it/ita/downloads.html

Costantini, E. A. C., Barbetti, R., Fantappiè, M., L'Abate, G., Lorenzetti, R., & Magini, S. (2013). Pedodiversity. In E. A. C. Costantini & C. Dazzi (Eds.), *The soils of Italy, World soils Book Series*. New York, NY: Springer. doi:10.1007/978-94-007-5642-7_6.

Costantini, E. A. C., Barbetti, R., Fantappiè, M., L'Abate, G., Lorenzetti, R., Napoli, R., … Rivieccio, R. (2014). The soil map of Italy: A hierarchy of geodatabases, from soil regions to sub-systems. In D. Arrouays, N. McKenzie, J. Hempel, A. C. Richer de Forges, & A. McBratney (Eds.), *Global soil map: Basis of the global spatial soil information system*. Leiden, The Netherlands: CRC Press. Taylor & Francis Group, LLC.

Costantini, E. A. C., & Dazzi, C. (2013). *The soils of Italy, World soils Book Series*. New York, NY: Springer. doi:10.1007/978-94-007-5642-7

Costantini, E. A. C., L'Abate, G., Barbetti, R., Fantappiè, M., Lorenzetti, R., & Magini, S. (2012). *Carta dei suoli d'Italia 1:1.000.000*. Firenze: CRA-ABP Centro di ricerca per l'agrobiologia e la pedologia. Retrieved from http://www.soilmaps.it/ita/downloads.html doi:10.13140/RG.2.1.4259.7848

Costantini, E. A. C., Urbano, F., Aramini, G., Barbetti, R., Bellino, F., Bocci, M., … Tascone, F. (2009). Rationale and methods for compiling an atlas of desertification in Italy. *Land Degradation & Development*, *20*, 261–276. doi:10.1002/ldr.908

Costantini, E. A. C., Urbano, F., Bonati, G., Nino, P., & Fais, A. (2007). *Atlante nazionale delle aree a rischio di desertificazione*. Roma: INEA. pp. 115. Retrieved from https://www.minambiente.it/sites/default/files/archivio/biblioteca/Atlante_desertificazione.pdf

Dobos, R. R., Sinclair, H. R. Jr., & Robotham, M. P. (2012). *National Commodity Crop Productivity Index (NCCPI) User Guide, Version 2*. USDA-NRCS. pp. 89. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050734.pdf

Dominati, E., Mackay, A., Green, S., & Patterson, M. (2014). A soil change-based methodology for the quantification and valuation of ecosystem services from agro-ecosystems: A case study of pastoral agriculture in New

Zealand. *Ecological Economics*, *100*, 119–129. doi:10.1016/j.ecolecon.2014.02.008

European Commission. (1998). *Carta Ecopedologica d'Italia*. Ufficio Europeo dei Suoli Joint Research Centre (JRC), Comune di Ricerca di Ispra (VA). Retrieved from https://esdac.jrc.ec.europa.eu/Library/Data/250000/Italy/MapRegions.htm

FAO. (2006). *Guidelines for soil description*. Rome: FAO. Retrieved from http://www.fao.org/3/a-a0541e.pdf

Filippi, N., & Italian Regional Soil Services. (2005). Soil mapping and soil monitoring: State of progress and use in Italy. In R. J. A. Jones, B. Houšková, P. Bullock, & L. Montanarella (Eds.), *Soil resources of Europe* (2nd ed., pp. 193–200). European Soil Bureau Research Report 9. European Commission – Joint Research Centre, Luxembourg. Retrieved from https://library.wur.nl/isric/fulltext/isricu_t4d6d164f_001.pdf

Global Soil Map. (2015). *Specifications tiered global soil map products. Release 2.4*. Retrieved from https://www.globalsoilmap.net/specifications

Greiner, L., Kellera, A., Grêt-Regamey, A., & Papritz, A. (2017). Soil function assessment: Review of methods for quantifying the contributions of soils to ecosystem services. *Land Use Policy*, *69*, 224–237. doi:10.1016/j.landusepol.2017.06.025

Grêt-Regamey, A., Weibel, B., Kienast, F., Rabe, S. E., & Zulian, G. (2015). A tiered approach for mapping ecosystem services. *Ecosystem Services*, *13*, 16–27. doi:10.1016/j.ecoser.2014.10.008

Haygarth, P. M., & Ritz, K. (2009). The future of soils and land use in the UK: Soil systems for the provision of land-based ecosystem services. *Land Use Policy*, *26*(Suppl. 1), S187–S197. doi:10.1016/j.landusepol.2009.09.01

Hengl, T., Heuvelink, G. B., Kempen, B., Leenaars, J. G., Walsh, M. G., Shepherd, K. D., … Tondoh, J. E. (2015). Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. *PLoS ONE*, *10*, e0125814. doi:10.1371/journal.pone.0125814

Hole, F. D., & Campbell, J. B. (1985). *Soil landscape analysis* (pp.214). London: Rowman & Littlefield Publishers.

ISPRA. (2012). Corine land cover (CLC) map of Italy. Retrieved from http://www.sinanet.isprambiente.it/it/sia-ispra/download-mais/corine-land-cover/

Jarvis, N. J. (2011). Simple physics-based models of compensatory plant water uptake: Concepts and eco-hydrological consequences. *Hydrology & Earth System Science*, *15*(11), 3431–3446. doi:10.5194/hess-15-3431-2011

Kempen, B., Brus, D. J., Stoorvogel, J. J., Heuvelink, G. B. M., & de Vries, F. (2012). Efficiency comparison of conventional and digital soil mapping for updating soil maps. *Soil Science Society of American Journal*, *76*(6), 2097–2115. doi:10.2136/sssaj2011.0424

Lagacherie, P., McBratney, A. B., & Voltz, M. (2007). *Digital soil mapping, volume 31: An introductory perspective (Developments in soil science)*. Amsterdam, The Netherlands: Elsevier. pp. 658. Retrieved from https://www.elsevier.com/books/digital-soil-mapping/lagacherie/978-0-444-52958-9

Leenaars, J. G. B., Claessens, L., Heuvelink, G. B. M., Hengl, T., Ruiperez González, M., van Bussele, L. G. J., … Cassman, K. G. (2018). Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-Saharan Africa. *Geoderma*, *324*, 18–36. doi:10.1016/j.geoderma.2018.02.046

Marras, F., De Leo, S., Giuca, S., Macrì, M. C., Monda, M., Sardone, R., & Viganò, L. (2018). Italian agriculture in figures 2017. pp. 133. Retrieved from http://antares.crea.gov.it:8080/documents/10179/240330/Itaconta%202017_%20ING_DEF_WEB2.pdf

McBratney, A. B., Mendonca Santos, M. L., & Minasny, B. (2003). On digital soil mapping. *Geoderma*, *117*, 3–52. doi:10.1016/S0016-7061(03)00223-4

Millennium Ecosystem Assessment (MEA). (2005). Current state and trends: Findings of the conditions and trends working group. In R. Hassan, R. Scholes, & N. Ash (Eds.), *Ecosystems and human well-being* (pp. 1–476). Washington, DC: Island Press. Retrieved from https://www.millenniumassessment.org/en/Condition.html

Miller, B. A. (2017). Geographic information systems and spatial statistics applied for soil mapping: A contribution to land use management. In P. Pereira, E. C. Brevik, M. Muñoz-Rojas, & B. A. Miller (Eds.), *Soil mapping and process modeling for sustainable land use management* (pp. 127–149). Amsterdam, The Netherlands: Elsevier.

Musters, P. A. D., & Bouten, W. (1999). Assessing rooting depths of an Austrian pine stand by inverse modeling soil water content maps. *Water Resource Research*, *35*, 3041–3048. doi:10.1029/1999WR900173

Pereira, P., Brevik, E. C., Muñoz-Rojas, M., & Miller, B. A. (2017). *Soil mapping and process modeling for sustainable land use management*. Amsterdam: Elsevier. doi:10.1016/B978-0-12-805200-6.00014-1

Schenk, H. J., & Jackson, R. B. (2002a). The global biogeography of roots. *Ecological Monographs*, *72*, 311–328. doi:10.1890/0012-9615(2002)072[0311:TGBOR]2.0.CO;2

Schenk, H. J., & Jackson, R. B. (2002b). Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. *Journal of Ecology*, *90*(3), 480–494. doi:10.1046/j.1365-2745.2002.00682.x

Schenk, H. J., & Jackson, R. B. (2009). ISLSCP II ecosystem rooting depths. In F. G. Collatz, G. Meeson, B. S. E. Los, B. de Colstoun, & D. Landis (Eds.), *ISLSCP initiative II collection* (pp. 1119–1124). Oak Ridge, TN: Oak Ridge National Laboratory Distributed Active Archive Center.

Soil Survey Manual. (2017). By Soil Science Division Staff United States Department of Agriculture Handbook No. 18 Issued March 2017.

Terrestrial Observation Panel for Climate. (1997). *GCOS/GTOS plan for terrestrial climate-related observations. Version 2. GCOS-32, WMO Tech. Doc. 796*. Geneva, Switzerland: World Meteorological Organization. 130 pp.

van der Biest, K., D'Hondt, R., Jacobs, S., Landuyt, D., Staes, J., Goethals, P., & Meire, P. (2013). Chapter 20 – EBI – an index for delivery of ecosystem service bundles. In S. Keune, N. Jacobs, & H. Dendoncker (Eds.), *Ecosystem services* (pp. 263–272). Boston, MA: Elsevier.

Wang-Erlandsson, L., Bastiaanssen, W. G. M., Gao, H., Jägermeyr, J., Senay, G. B., van Dijk, A. I. J. M., … Savenije, H. H. G. (2016). Global root zone storage capacity from satellite-based evaporation. *Hydrology and Earth System Sciences*, *20*(4), 1459–1481. doi:10.5194/hess-20-1459-2016

Yang, Y., Donohue, R. J., & McVicar, T. R. (2016). Global estimation of effective plant rooting depth: Implications for hydrological modeling. *Water Resources Reseaarch*, *52*, 8260–8276. doi:10.1002/2016WR019392

Zeng, X. B. (2001). Global vegetation root distribution for land modeling. *Journal of Hydrometeorology*, *2*, 525–530. doi:10.1175/1525-7541(2001)002<0525:GVRDFL>2.0.CO;2

Zevenbergen, L. W., & Thorne, C. R. (1987). Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, *12*, 47–56. doi:10.1002/esp.329012010