

Action B1.3
**Guidelines for assessing soil
ecosystem services in urban
environment and their
management**

REPORT

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Guidelines for assessing soil ecosystem services in urban environment and their management

1. INTRODUCTION

Urban soils are deeply influenced by human activities. They consist of materials different from those of nearby agricultural or natural areas, due to mechanical disturbance, supply or removal of material, contamination with exogenous materials (plastics, asphalt, pollutants, etc.). They are the result of urbanization activities that involve total or partial sealing of the surfaces (Morel et al. 2005).

The development of urban soils is controlled by the same factors as natural soils, with a clear and important prevalence of the anthropic factor. The survey of urban soils therefore follows the same criteria of surveying natural or agricultural soils, taking into account that the anthropic disturbance in addition to being prevalent acts in a very short time. This causes a strong heterogeneity in the spatial distribution of the soils and of their characteristics that is problematic to solve in a detailed soil map.

Human disturbed soils are classified (FAO World Reference Base For Soil Resources, IUSS - Working Group WRB, 2014) as:

- **Anthrosols**: soil that has been formed or heavily modified due to long-term human activity, such as from irrigation, addition of organic waste or wet-field cultivation used to create paddy fields
- **Technosols**: are dominated by their technical origin. They contain either a significant (20% or more) amount of artefacts or some sort of geotechnical liner, or are sealed by technic hard rock (hard material created by humans, having properties unlike natural rock).

Urban soils perform the same functions as a natural soil contributing to the provision of Ecosystem Services. However, the degree of disturbance to which they are subjected, the level of sealing and the type of coverage have an influence that needs to be described in detail and taken into account.

Given the great variability of the urban environment and the differences between different urban environments, there are still no standardized references for the survey and mapping of urban soils. There are some experiences, such as the map of the city of Berlin (https://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/dinh_01.htm) and of New York City (<http://www.soilandwater.nyc/urban-soils.html>).

Within the SOS4LIFE project, a methodology has been developed for defining urban soil mapping units in the study case of the town of Carpi (MO), based on the type of "natural" soils below the urban fabric, the urban typologies and the land cover of unsealed soils. Considering that most of the SEs in urban areas are provided by green areas, the assessment of soils and related functionality has been concentrated in gardens and parks, sports fields and on peri-urban agricultural areas. The gardens in private allotments were not considered, having verified the high degree of impermeabilization of the same (driveways, parking lots, access ramps to garages, etc.). However, even these soils, although strongly altered, maintain some functionalities. The SEs considered are therefore generally underestimated for the entire city.

2. ASSESSING SOIL BASED ECOSYSTEM SERVICES

2.1 Mapping urban soils

Prior knowledge of soils, of their properties and distribution in the urban space is required in order to assess and eventually map their ecosystem services (ESs). Depending on the goal of the investigation and on resources availability, the necessary soil data can result from *ad hoc* urban soil surveys or from existing soil databases and maps.

2.1.1 Ad hoc urban soil survey

Due to the high variability of urban soils and their characteristics, it is unlikely to define precisely soil typologies in urban areas. Standard soil surveying techniques are not suited for the urban environment and specific soil surveying techniques have to be followed. We need to have practical instruments able to support urban planning, taking into account the ESs provided by soils. These instruments need to be as simple as possible so that every municipality can easily adopt them in their planning policies.

Assuming that urban soils development is strongly affected by human activities, we can define “urban pedolandscape units” taking into account the “natural soils” underlying the town and its urbanistic structure, degree of sealing and land use. An example relative to the town of Carpi is shown in

Figure 1.

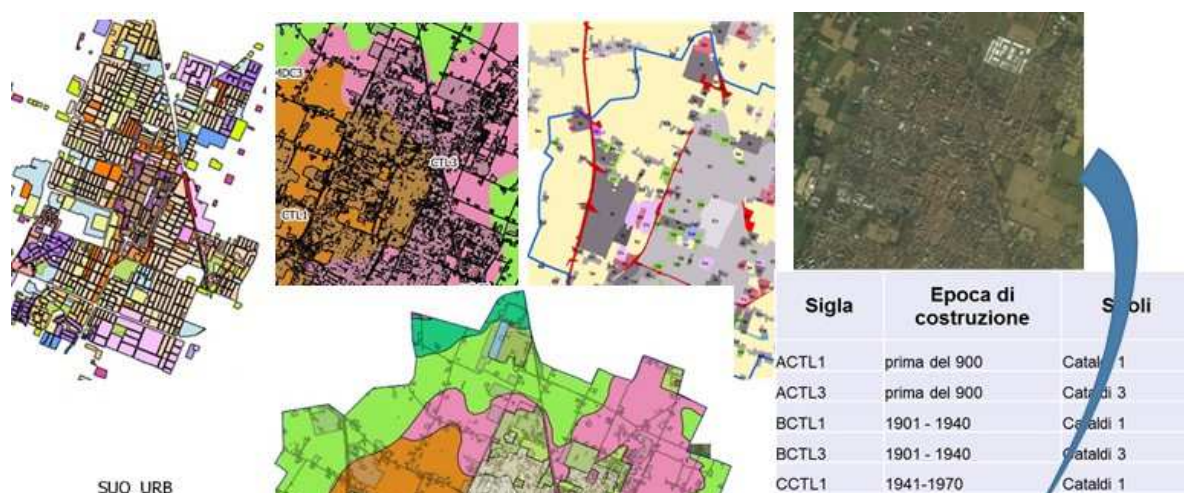




Figure 1. Definition of preliminary urban pedolandscape units in the municipality of Carp, Emilia Romagna (NE Italy).

In this case, the different urban typologies have been overlaid to soil map (1:50,000) obtaining a number of preliminary urban pedolandscape units. Green areas soils must then be characterised according for each pedolandscape unit, taking into account the main land use types, e.g. i) urban agriculture, ii) gardens and parks; iii) sport fields; iv) industrial green spaces; v) roundabouts and roadsides green; vi) abandoned areas.

As for **soil sampling** a consistent number of observations must then allocated in the different units in order to have a complete coverage of the different soil conditions within the urban fabric. The number of observations per mapping unit will be proportional to the area of the units (stratified random sampling) and will depend upon resources constrains. As a result, very small map units cannot be sampled. Accessibility to sampling sites must be verified in advance, as it is very likely that not all green areas would be granted access to the surveyors. The choice of sampling sites falls obviously on green spaces not occupied by buildings or roads such as public parks, medium-large private gardens, green sports fields, court areas belonging to schools, flowerbeds, roadsides and roundabouts, urban agricultural areas, woody ruderal sites, and abandoned areas. It is recommended to supplement each sampling site with a set of photographs that document: augering, soil cover, landfill (when present), views of the area with 4 perspectives (N, S, E, O) and a panoramic photo. The soil cores from augering are to be described following soil survey standards as those in the manual provided by the Soil Survey Service of Emilia-Romagna (<http://ambiente.regione.emilia-romagna.it/it/geologia/temi/suoli/pubblicazioni-on-line-sul-suolo>). The depth of the auger hole must reach 150 cm, unless obstacles are met (gravel, lithic or paralithic contact, extremely dry conditions). The collection of soil samples must differentiate the topsoil horizon(s) (0-30 cm) from the underlying subsoil horizons; the number of samples per sampling site will depend upon resources availability and the specific goals of the assessment (e.g. urban soils mapping, ecosystem services assessment).

The assessment of the ecosystem services provided by urban soils, either qualitative or quantitative relies on the availability of soil analytical data (Table 1. Soil parameter, analytical methods and references. *: required for soil ecosystem services indicator assessment.), both from field and from laboratory in order to derive indicators of ecosystem services provision (Blanchart et al., 2018). To this goal, a core set of laboratory analytical data is required encompassing at least: i) **soil texture** (at least three fractions, sand, silt and clay) and **coarse fragments** ($\varnothing > 2$ mm), ii) **soil organic carbon content**, and iii) **pH**. Depending upon resources availability and upon the goal of the assessment, additional soil routine analyses can address total nitrogen, calcium carbonates content, cation exchange capacity, exchangeable basis (Ca, Mg, Na and

K), total base saturation, exchangeable Na percentage, and heavy metals concentration (**Errore. L'origine riferimento non è stata trovata.**). Among the listed parameters, **cation exchange capacity** is required for ecosystem service indicator assessment, but it can be estimated via PTF from clay and organic carbon content. All analyses must conform to the official standard analytical methods (e.g DM 13/09/1999, Approval of "Ufficial methods of soil chemical analyses").

Among the field analyses, it would be preferably to assess topsoil **bulk density** (by core sample method), and **saturated hydraulic conductivity** (e.g. by using a double head permeameter). These latter can also be estimated resorting to **pedotransfer functions (PTFs)** using as inputs soil textural fractions and organic carbon content. Similarly, water retention properties required for the assessment of soil ecosystem services, namely **air entry pressure** (cm), and **available water content** (AWC vol./vol., given by the difference between WC at field capacity, WC_{FC} , and water content at wilting point, WC_{WP}) can be assessed resorting to PTFs. To this aim, it is recommended to resort to locally calibrated PTFs whenever available (e.g. Ungaro et al. 2005; Ungaro et al., 2014)

As for soil biodiversity, the **Soil Biological Quality Index** is defined based on micro arthropods (**QBS-ar**, Parisi, 2001). These organisms present a complex series of adaptations to life in the edaphic environment, are sensitive to the state of suffering of a soil, and can be used as quality bio indicators.

Soil animals have different degrees of adaptation to hypogeal life, such as absence of visual organs, elongation and flattening of the body, shortening of sensory and locomotor appendices, reduction or disappearance of some appendages such as the furca (organ used for jumping) in the *Collembola* or the metathoracic wings in the *Coleoptera*, the presence of sensory organs to detect the degree of humidity, the depigmentation or the possible cryptic pigmentation to be confused with earth particles like in mites, the reduction or disappearance of sensory organs that absorb light radiations (Menta, 2012).

The various groups are defined by biological forms characterized by the same series of converging characters. These organisms have thus adapted themselves to the edaphic environment, and can no longer survive outside it (Parisi et al., 2005).

Parameter	Unit	Method	Reference
Sand 2000-100 μ m	%	Sieve	D.M. 13/09/1999. Method II.5
Sand 100- 50 μ m	%	Sieve	D.M. 13/09/1999. Method II.5
Sand 2000-50 μ m*	%	Sieve	
Silt 50-20 μ m	%	Pipette or hydrometer	D.M. 13/09/1999. Method II.5, II.6
Silt 20-2 μ m	%	Pipette or hydrometer	D.M. 13/09/1999. Method II.5, II.6
Silt 50-2 μ m*		Pipette or hydrometer	D.M. 13/09/1999. Method II.5, II.6
Clay <2 μ m*	%	Pipette or hydrometer	D.M. 13/09/1999. Method II.5, II.6
pH *	-	in H ₂ O 1:2,5	D.M. 13/09/1999. Method III.1
Total CaCO ₃	%	Gas volumetric	D.M. 13/09/1999. Method V.1
Active CaCO ₃	%	Droineau	D.M. 13/09/1999. Method V.2
Organic C*	%	Elemental analyzer	D.M. 13/09/1999. Method VII.1
Total N	per thousand	Kjeldhal or Elemental analyzer	D.M. 13/09/1999. Method XIV.3 o XIV.1
CEC**	meq/100g	BaCl ₂ pH 8,1 for calcareous soils, NH ₄ acetate for acid soils	D.M. 13/09/1999. Method XIII.2, XIII.1
Exchangeable Ca	meq/100g	BaCl ₂ pH 8,1 for calcareous soils, NH ₄ acetate for acid soils	D.M. 13/09/1999. Method XIII.5 XIII.4
Exchangeable Mg	meq/100g	BaCl ₂ pH 8,1 for calcareous soils, NH ₄ acetate for acid soils	D.M. 13/09/1999. Method XIII.5 XIII.4
Exchangeable K	meq/100g	BaCl ₂ pH 8,1 for calcareous soils, NH ₄ acetate for acid soils	D.M. 13/09/1999. Method XIII.5 XIII.4
Exchangeable Na	meq/100g	BaCl ₂ pH 8,1 for calcareous soils, NH ₄ acetate for acid soils	D.M. 13/09/1999. Method XIII.5 XIII.4
TBS total base saturation	-	Derived parameter = exchangeable basis/CEC *100	
ESP Exchangeable Na percentage	-	Derived parameter = exchangeable Na /CSC *100	

Parameter	Unit	Method	Reference
Heavy metals (As, Cd, Cr, Cu, Ni, Pb, Sb, Sn, V, Zn)	mg/kg	Extraction in <i>aqua regia</i> + ICP-MS	UNI-EN 13346:2002 / EPA 6020 EPA 3051A 2007 /EPA 6020 EPA 3051A 2007 /EPA 6010 UNI EN 16174:2012 B+UNI EN 16171:2016

Table 1. Soil parameter, analytical methods and references. *: required for soil ecosystem services indicator assessment. **: required for soil ecosystem services indicator assessment but derivable via PTFs.

Sampling for QBS-ar must take into account the information on land use, the data on the averages of rainfall preceding the time of sampling, and the soil humidity at the time of sampling. At each sampling site, three replicas are taken consisting of distinct cubic clods of 10 cm on each side, collected at points 5 to 10 meters apart, trying to encompass as much as possible the observed field variability. After removing any litter or herbaceous cover, the samples are placed in plastic bags in which a reserve of air must remain.

The **description of soil profiles** is required only for urban soils mapping purposes, as their field description and analysis can provide the information necessary to highlight the relationship between *in situ* soil materials and exogenous material, either soil or of anthropic nature. In this way, it becomes possible to assess the actual nature, degree and extent of soil disturbance due to different anthropic activities and how this is likely to affect the provision of ecosystem services. The number of soil profiles (that can be excavated or be observed along already open ditches) will depend upon the number and the area of the mapping units identified and from the analytical data from auger-holes samples. Furthermore, data from soil profile will support the definition of **urban soil mapping units**; soils are classified according to WRB (IUSS - Working Group WRB, 2014), which is more suitable and versatile of Soil Taxonomy (Soil Survey Staff, 2014) in the classification of urban soils.

Also useful to the aim of characterizing and mapping urban soil is the assessment of the **degree of soil sealing** of each mapping unit. The assessment can be based either on technical documentation at municipality scale if available, or resorting to the last update (2018) of the CORINE land cover map (<https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download>) or, even better, to the soil sealing map yearly updated by ISPRA at a 10 m resolution (<http://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/consumo-di-suolo/carta-nazionale-consumo-suolo>).

The soil mapping units in the final urban soil map will then result from a refinement of the preliminary urban pedolandscape units based on the evidences stemming from analytical results and soil profiles description, eventually supported by the available information on land use/land cover, degree of soil sealing, digital elevation model, and multi-temporal aerial photos series.

2.1.2 Using existing soil information: examples for Emilia Romagna region and Italy

In case an ad hoc survey is not possible, ESs can be assessed at general scale using existing soil and ancillary information. The needed minimum information is reported in table 3.

MAPS	NECESSARY?	NOTES
Detailed or semi-detailed soil map (scale 1:25.000-1:50.000)	Y	
Detailed or semi-detailed Land Capability map (scale 1:25.000-1:50.000)	Y	
Detailed or semi-detailed land use map (scale 1:25.000-1:50.000)	Y	CORINE LAND COVER 4°level
Benchmark soil profiles, with analyses for texture, organic carbon content, CEC.	NO	Only in case the following maps are not available
Map of texture and coarse fragments content of topsoil	Y	Either maps of the first 100 cm.
Map of texture and coarse fragments content of subsoil	Y	
Map of organic carbon content in topsoil	Y	Either maps of the first 100 cm.
Map of organic carbon content in subsoil	Y	
Map of organic carbon stock in topsoil	NO*	Either maps of the first 100 cm.

Map of organic carbon stock in subsoil

NO*

Table 2. Information layers for ESs assessment. Soil organic carbon stock can be calculated from SOC and bulk density (calculated via PTF)

Many Italian Regions¹ hold this information, e.g. Emilia-Romagna², Veneto³, Piemonte⁴, Lombardia⁵, Toscana⁶, Campania⁷. Some Regions, as Basilicata⁸ and Calabria⁹, hold this information only at general scale (1:250,000).

As for Carbon stock, the recently produced Global Soil Organic Carbon Stock map (FAO, 2017) is available at <http://54.229.242.119/GSOCmap/>.

Using locally calibrated **pedotransfer functions** (PTFs) the following data required for the assessment can be calculated:

- bulk density (Mg m^{-3}),
- saturated hydraulic conductivity (mmh^{-1}),
- air entry pressure (cm),
- available water capacity (vol./vol.), derived from the estimated water content at 333 and 1500 cm tension,
- cation exchange capacity ($\text{cmol}_c \text{ kg}^{-1}$)

2.1.3 Tutorial for consulting websites of Emilia-Romagna Region.

All the cited information layers are available for Emilia-Romagna region. This tutorial aims at guiding users in retrieving the available soil data on regional portals.

DGCTA minERva portal (in Italian) aims at divulging and distributing all the information and data produced and owned by DG Land and Environment Care to the wide public and to the staff of local and national public administrations. Through the portal, it is possible to access all the regional thematic and applicative maps, including soil maps.

Access to the web portal is through the following URL::

<https://datacatalog.regione.emilia-romagna.it/catalogCTA/>

¹ <http://ambiente.regione.emilia-romagna.it/it/geologia/temi/suoli/il-suolo-nel-web-siti-delle-regioni-italiane>

² <http://ambiente.regione.emilia-romagna.it/it/geologia/temi/suoli/cartografie>

³ <http://geomap.arpa.veneto.it/people/profile/suoli?limit=100&offset=0>

⁴ <http://www.sistemapiemonte.it/cms/privati/agricoltura/servizi/383-carta-dei-suoli-1-50-000>

⁵ <https://www.dati.lombardia.it/browse?q=basi%20informativa%20suoli&sortBy=relevance>

⁶ <http://www502.regione.toscana.it/geoscopio/pedologia.html>

⁷ <http://www.agricoltura.regione.campania.it/pedologia/suoli.html>

⁸ <http://www.basilicatanet.it/suoli/derivate.htm>; <http://www.basilicatanet.it/suoli/comuni.htm>

⁹ <http://www.arsacweb.it/pubblicazione/le-novita-della-pac-per-il-2015-e-gli-obblighi-di-condizionalita-per-le-aziende-agricole/>

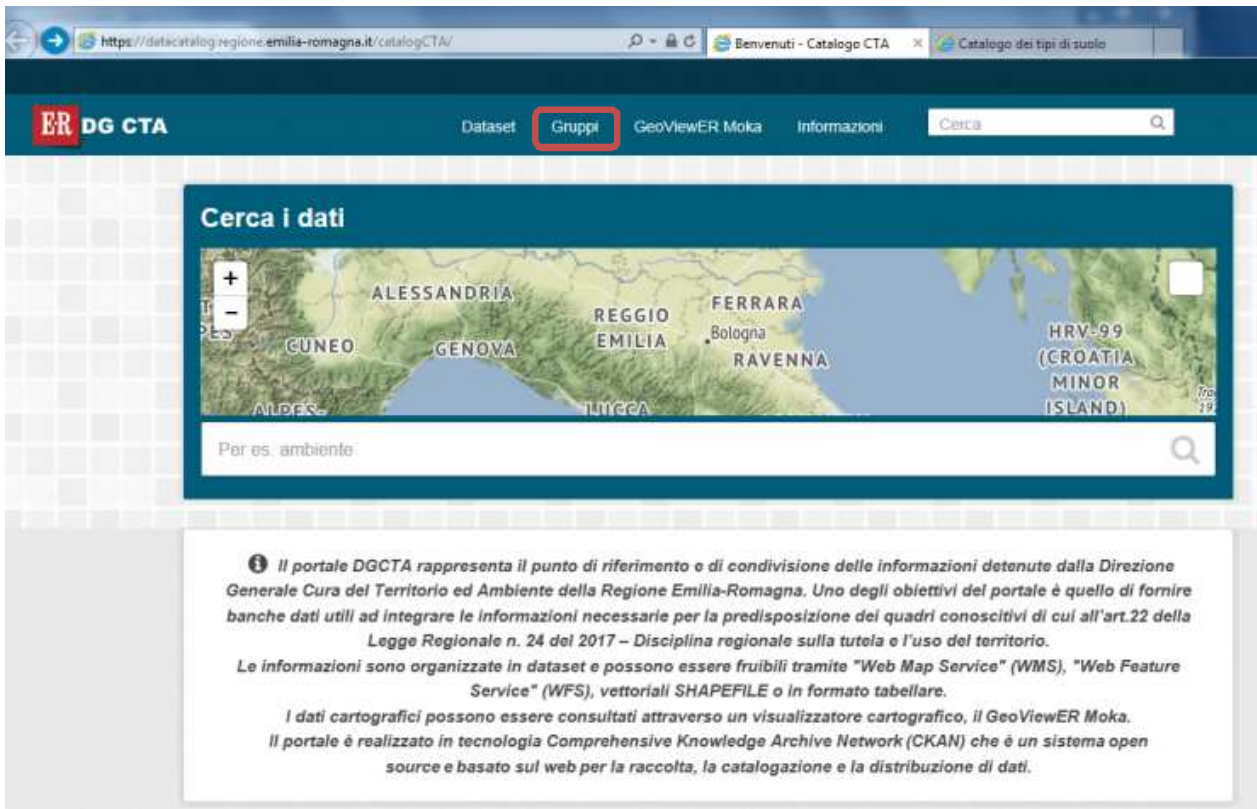


Figure 2. Portal minERva: homepage interface



In the homepage (Figure 2), the menu in upper bar allows to access and navigate the contents of the portal. Selecting the menu “Gruppi” the user has access to 33 different catalogs (<https://datacatalog.regione.emilia-romagna.it/catalogCTA/group>); on the second page the group “Suolo” is available to access soil related data and maps (Figure 3).

At the page “Suolo”, 14 datasets/maps are available (Figure 4); these are available in different formats (HTML, WMS, KML, ESRI), but they all refer to the same page where all the formats made available to the user are listed (in Figure 5, the example for topsoil texture is reported).

Figure 3. Icon for SOIL data/information

Home / Gruppi / Suolo

Suolo

Sostenitori: **0** Dataset: **14**

Gruppi

Suolo (14)

Tag

Suolo (14)

Stock Carbonio (4)

Pianificazione Agri... (4)

Gas-A-Effetto-Serra (4)

Carbonio Organico (4)

Proprietà Chimiche (3)

Fertilità Del Suolo (3)

Ambiente (3)

Salinità Del Suolo (2)

Protezione Delle Acque (2)

Mostra altro Tag

Formati

Wms (14)

Html (14)

Shp (12)

Kmz (2)

Html_Simpl (1)

Dataset Flusso di attività Informazioni

Cerca dataset...

14 dataset trovati Ordina per: Rilevanza

Carta del Fondo Naturale a scala 1:250.000 della pianura emiliano-romagnola - Cr, Cu, Ni, Pb, V, Zn

Rappresenta la distribuzione areale nel subsoil (90-140 cm di profondità) del contenuto di 6 metalli (Cr, Cu, Ni, Pb, V, Zn) nei suoli ad uso agricolo. Tale profondità è...

KMZ HTML WMS html_simpl

Carta del Fondo naturale-antropico della Pianura emiliano-romagnola, scala 1:250.000 - As, Cr, Cu, Ni, Pb, Sn, V, Zn

La "Carta del contenuto di Fondo naturale-antropico" rappresenta la distribuzione areale nel topsoil (20-30 cm di profondità) di alcuni metalli potenzialmente tossici [As, Cr,...

KMZ HTML WMS

Carta dei suoli – Pianura, basso e medio Appennino emiliano-romagnolo, scala 1:50.000 - Edizione 2018

Descrive i suoli e la loro distribuzione geografica nella pianura, in gran parte (93%) del basso Appennino (collina) e una piccola parte (10%) del medio Appennino della regione...

WMS HTML Esri Shape

Carta dei Gruppi Idrologici della pianura emiliano-romagnola

La carta descrive la distribuzione areale dei Gruppi Idrologici dei Suoli attraverso i poligoni della Carta dei Suoli di pianura in scala 1:50.000. Ogni poligono è descritto...

WMS Esri Shape HTML

Salinità dei suoli della pianura emiliano-romagnola tra 0-50 cm

La carta della salinità descrive lo stato di salinità dei suoli tra 0-50 cm. E' una rappresentazione derivata da analisi geostatistica a partire da dati puntuali raccolti nella...

WMS Esri Shape HTML

Salinità dei suoli della pianura emiliano-romagnola tra 50-100 cm

La carta della salinità descrive lo stato di salinità dei suoli tra 50-100 cm. E' una prima rappresentazione derivata da analisi geostatistica a partire da dati puntuali...

WMS Esri Shape HTML

Figure 4. Partial list of the SOIL available datasets

Tessitura dei suoli della pianura emiliano-romagnola - strato 0-30 cm, scala 1:50.000

Sostenitori
0

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Risorse

- Tessitura_0_30_cm** (WMS) [Esplora](#)
- Tessitura 0-30 cm** (DATA) [Esplora](#)
- Cartografia dei suoli** (HTML) [Anteprima](#) [Download](#)
- Cartpedo** (HTML) [Esplora](#)
- Suoli e pianificazione** (HTML) [Esplora](#)

argilla fertilità del suolo proprietà fisiche suolo tessitura del suolo

Figure 5. Retrieving regional data: example for topsoil texture

There are several options for accessing data:

- first option allows visualising the layer in Moka viewer (preview) and downloading in **WMS** format
- second option allows downloading as **shapefile**
- third option allows visualising the layer on a web-gis, “**Cartografia dei suoli**”, together with other thematic maps. On this site it is possible to download the description of the 1:50,000 soil map polygons and the analyses of the reference soil profile.
- Fourth option allows visualising the layer on the web-gis “**I suoli dell’Emilia-Romagna**” (CARTPEDO), in GOOGLE EARTH environment.
- Fifth option re-address to the webpages of the Soil Survey Service of Regione Emilia-Romagna.

The 1:50,000 soil map (2018) is available in vectoral format for 71% of the regional territory (plain areas, hills and low mountains). Land capability map (2010) is available for plain areas only. Maps of texture, organic carbon content (%) and stock (Mg ha^{-1}) are available for topsoil, I (0-30 cm) and subsoil (30-100 cm), and are referred to a 500 x 500 m grid in plain areas. Soil organic carbon and stock are available also for hills and mountains in a 1000x1000 m grid.

2.2 Soil ecosystem services assessment

The methods for calculating the indicators is described in the project deliverable (Action B1.2) “*Misurazione a scala comunale degli impatti del consumo dei suoli e valutazione dei servizi ecosistemici*” (in Italian), and in the article “*A methodological framework to assess the multiple contributions of soils to ecosystem services delivery at regional scale*” (Calzolari et al., 2106), both available at the SOS4LIFE website (<http://www.sos4life.it/documenti/>). The considered ecosystem services, the underpinning soil functions and the input data required for their assessment are summarized in Table 3. Ecosystem services (ESs), underpinning soil functions, indicators and input data. ^aMEA 2005; ^bDominati et al. 2010; ^cEuropean Commission (EC), 2006.

ESs categories ^a	Soil contribution to ESs ^b	Soil function ^c	Indicator	Input data	Code
Supporting	Habitat for soil organisms	Biodiversity pool	Potential habitat for soil organisms	Land use Bulk density Organic C	BIO
Regulation	Nutrient and pollutants retention and release; Natural attenuation (potential)	Storing filtering and transforming nutrient, substances and water	Cation exchange capacity Soil reaction Rooting depth	Organic C Clay content pH (0-30) Average shallow groundwater depth	BUF
Regulation	Microclimate regulation (potential)	Storing filtering and transforming nutrient, substances and water	Soil evaporation potential	Available water capacity Average shallow groundwater depth	CLI
Regulation	Carbon sequestration (potential)	Carbon pool	Carbon sequestration actual	Organic C and bulk density (0-30 cm)	CST
Provisioning	Food provision (potential)	Biomass production	Land capability (LC) map	LC classes and intergrades	PRO
Regulation	Water regulation /Runoff -flood control (potential)	Storing filtering and transforming nutrient, substances and water	Infiltration capacity	Hydraulic saturated conductivity Air entry point	WAR
Regulation (Provisioning)	Water regulation - Water storage (potential)	Storing filtering and transforming nutrient, substances and water	Water content at field capacity Presence of water table	Field Capacity (-33 kPa) Average shallow groundwater depth	WAS

Table 3. Ecosystem services (ESs), underpinning soil functions, indicators and input data. ^aMEA 2005; ^bDominati et al. 2010; ^cEuropean Commission (EC), 2006.

The calculation results for each indicator are standardised as numbers in the range 0 to 1 (Wu et al., 2013) resorting to an interval normalization as follows:

$$X_{i\ 0-1} = (X_i - X_{\min}) / (X_{\max} - X_{\min})$$

where $X_{i\ 0-1}$ is the standardised [0-1] value, X_i is the actual value, X_{\min} and X_{\max} are the minimum and the maximum respectively of each considered variable in the dataset. The formula gives values close to 1 to higher values of the considered input variable or indicator; the lowest value, 0, does not indicate that the input variable value is equal to 0 or that the function is not provided, but that it is the lowest in the considered area. It is of pivotal importance then to tailor the assessment to the scale of investigation and to the goal of the analyses, as results will be deeply affected by the degree of variability observed in soil measured and estimated soil properties, whose ranges are strongly scale dependent and different for each variable. The

calculation procedures for each indicator are summarized in Table 4. Calculation procedures for the selected indicators of soil based ecosystem services.

Code	Input data	Calculation																																												
BIO	QBS _{ar} as a function of dominant Land use (High= 1; Medium= 0.5; Low= 0.25) Bulk density, BD (mg ha ⁻¹) Organic C, OC (%)	$BIO_{0-1} = (\text{LogOC}_{0-1} - BD_{0-1}) + QBS_{ar\ 0-1}$																																												
BUF	CSC (cmolc/kg) as a function of Organic C (%) and clay content (%) CEC = 6.332 +0.404 Clay + 1.690 OC (R ² = 0.75) pH Average shallow groundwater depth, WT (cm)	$BUF_{0-1} = \text{Log CSC (pH; sk)}_{0-1}$ <i>with pH<6.5 reduction by 0.25 or 0.5 depending on CSC and skel>30% by 0.25</i> for water table deeper than 100 cm, and $BUF_{0-1} = \text{Log CSC (pH; sk)}_{0-1} * WT/100$ in case of occurrence of a shallow water table within the first 100 cm of soil depth, being WT the average water table depth (cm).																																												
CLI	Available water capacity, AWC (vol/vol) AWC= WC _{FC} -WC _{WP} Average shallow groundwater depth, WT (cm)	$CLI_{0-1} = \text{logAWC}_{0-1} + WT_{0-1}$																																												
CST	Organic C, OC (%) Bulk Density, BD (Mg m ⁻³)	$CST_{0-1} = \text{log (OC * BD)}_{0-1}$																																												
PRO	LC classes and intergrades	<table border="1"> <thead> <tr> <th>LCC</th> <th>I</th> <th>I/II</th> <th>II</th> <th>II/I</th> <th>II/III</th> <th>II/III/IV</th> <th>II/IV</th> <th>III</th> <th>III/II</th> <th>III/II/IV</th> </tr> </thead> <tbody> <tr> <td>Score</td> <td>1</td> <td>0.95</td> <td>0.8</td> <td>0.9</td> <td>0.7</td> <td>0.65</td> <td>0.55</td> <td>0.6</td> <td>0.65</td> <td>0.57</td> </tr> <tr> <th>LCC</th> <th>III/IV</th> <th>III/VI</th> <th>IV</th> <th>IV/II</th> <th>IV/III</th> <th>IV/VI</th> <th>V</th> <th>V/II</th> <th>VI/IV</th> <th>VIII</th> </tr> <tr> <td>Score</td> <td>0.5</td> <td>0.3</td> <td>0.4</td> <td>0.5</td> <td>0.5</td> <td>0.27</td> <td>0.3</td> <td>0.4</td> <td>0.25</td> <td>0</td> </tr> </tbody> </table>	LCC	I	I/II	II	II/I	II/III	II/III/IV	II/IV	III	III/II	III/II/IV	Score	1	0.95	0.8	0.9	0.7	0.65	0.55	0.6	0.65	0.57	LCC	III/IV	III/VI	IV	IV/II	IV/III	IV/VI	V	V/II	VI/IV	VIII	Score	0.5	0.3	0.4	0.5	0.5	0.27	0.3	0.4	0.25	0
LCC	I	I/II	II	II/I	II/III	II/III/IV	II/IV	III	III/II	III/II/IV																																				
Score	1	0.95	0.8	0.9	0.7	0.65	0.55	0.6	0.65	0.57																																				
LCC	III/IV	III/VI	IV	IV/II	IV/III	IV/VI	V	V/II	VI/IV	VIII																																				
Score	0.5	0.3	0.4	0.5	0.5	0.27	0.3	0.4	0.25	0																																				
WAR	Hydraulic saturated conductivity, Ksat (mmh ⁻¹) Air entry point , PSle (cm)	$WAR_{0-1} = \text{logKsat}_{0-1} - PSle_{0-1}$																																												
WAS	Field Capacity (-33 kPa), WC _{FC} (vol/vol) Average shallow groundwater depth, WT (cm) Sk, coarse fragments (Ø >2 mm, vol/vol)	$WAS_{0-1} = (WC_{FC} * 1 - sk)_{0-1}$ for water table deeper than 100 cm, and $WAS_{0-1} = (WC_{FC} * 1 - sk) * WT/100$ for water table within the first 100 cm																																												

Table 4. Calculation procedures for the selected indicators of soil based ecosystem services.

As for **BIO**, we defined three qualitative classes for QBS_{ar} based on data from literature (Menta et al., 2008) and depending upon dominant land use: High (QBS_{ar}, 150-250) for permanent meadows and pastures, woodlands, and peatlands; Medium (QBS_{ar}, 100-150) for agricultural lands under rotation with meadows and minimum tillage; and Low (QBS_{ar}, 60-100) for other land uses. QBS_{ar} in sealed or strongly anthropized is equal to 0 (Prokop et al, 2011).

For the assessment of **PRO** we used as a proxy of agricultural production the **Land Capability Classification** class and intergrades, transforming the original ordinal scale into a continuous one with a score ranging from 1 to 0 (Table 4). The LCC was originally developed by the Soil Conservation Service of the U.S. Department of Agriculture (Klingebiel and Montgomery, 1961), and adapted to local soil conditions (Guermendi, 2000). The LCC map is available at the scale 1:50,000 (Regione Emilia Romagna, 2010) for the plain areas (https://geo.regione.emilia-romagna.it/cartpedo/carte_tematiche.jsp?tem=2#tem2).

For the assessment of the **BUF**, **CLI** and **WAS** indicator, the presence of a **shallow water table** within 100 cm depth is taken into account. Floodplain soils depth is always greater than 100 cm, but the presence of a shallow water table can locally reduce the rooting depth; in this case the depth of shallow water table in the first 100 cm of soil was taken into account for decreasing the overall attenuation and storage capacity of the soil. This information was derived by the long term average depth of the shallow water table map (Figure 6) available for the plains of Emilia Romagna (Barca et al., 2014; Calzolari and Ungaro, 2012).

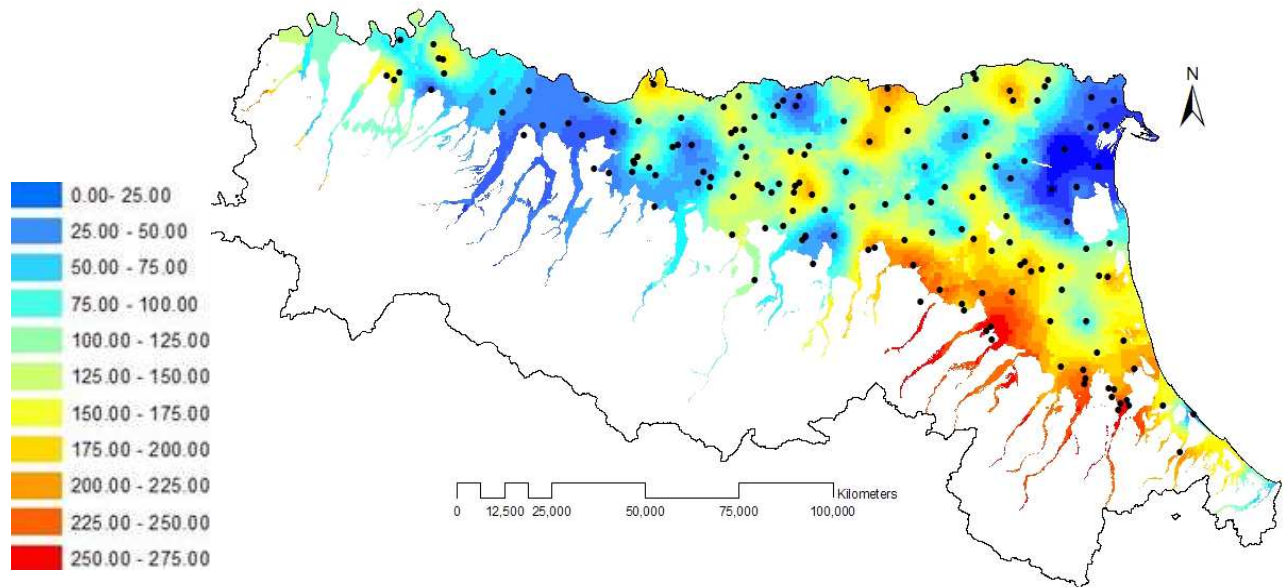


Figure 6. Long-term average depth of the shallow water table.

Assuming that the soils sealed by urbanisation are not capable to provide any ecosystem service, as they lost their multi-functionality, we suggest to use the yearly updated map of soil sealing provided by ISPRA at a 10 m resolution () to weigh the indicators values. For example, adopting a regular grid with cell size depending on the scale of investigation, the relative fraction (range 0-1) occupied by built areas (URB) is considered and used to rescale each indicator as follows:

$$\text{Indicator_final} = \text{Indicator} * \text{URB}_{0-1}$$

3. MANAGING

As discussed, urban soils provide important ecosystem services that can be of high quality. They also may provide disservices, mostly linked to pollution risk and the associated impacts on human health.

Soil survey and soil functions and ecosystem services assessment provide urban planners with a tool for an aware approach to planning, taking into consideration the role of soil in the urban environment. Moreover, the assessment of the services provided by soil and of their overall quality should lead the urban planner choices as regard policies of densification. Even if urban densification may represent an alternative to urban sprawl, the best performing soils should be protected.

Whatever the planning choices, urban green areas should be managed in a sustainable way (FAO, 2017), which in an urban environment means reducing at most the hamper for soil functioning.

The following constitutes general, and not exhaustive, guidelines to address major soil threats in urban areas.

Enhance soil organic matter content

Soil organic matter plays a central role in maintaining soil functions and preventing soil degradation. Moreover, urban soils may stock organic carbon contributing in reducing CO₂ emissions.

- i) In parks and garden: increasing biomass production (by increasing water availability for plants using methods that maximize water-use efficiency and minimize soil erosion and nutrient leaching, balancing fertilizer applications and green manures); implementing urban forestry; managing crop residues, minimising their removal,
- ii) In flowerbeds: Increasing organic matter using organic amendments, compost, and applying mulches or providing the soil with a permanent cover;
- iii) In roadside green: using cover vegetation resistant to trampling.
- iv) In agricultural allotments (urban vegetable gardens, residual agricultural fields), support management practices such as cover crops, reduced- or no-tillage practices, organic fertilisation.

Prevent and minimize soil contamination

Soil may filter, fix and neutralize, but also release pollutants, especially in urban areas. Therefore, prevention of soil contamination remains the best way to maintain healthy soils and human health. Monitoring pollution sources and potentially polluted soils will help in applying prevention policies and regeneration strategies.

Preserve and enhance soil biodiversity

Soils provide large reservoirs of biodiversity, and soil organisms underpin most of the soil based ecosystem services. Due to the presence of a wide variety of microhabitats with different features evolving with time, urban soils may provide a high level of biodiversity. As urban soil biodiversity is strongly influenced by the degree of disturbance, management can help in preserving and enhancing it.

- i) In all green areas: restoring plant biodiversity, thereby favouring soil biodiversity
- ii) In parks and gardens: using nitrogen fixing leguminous species.
- iii) In all green areas: adopting soil organic matter enhancing management practices
- iv) In agricultural allotments: crop rotation, inter-cropping, and preservation of field margins, hedges and biodiversity refuges;
- v) Reducing the use of pesticides.

Prevent and mitigate soil compaction

Soil compaction is related to the degradation of soil structure and results in an increase in soil bulk density. Soil compaction reduces soil aeration, water drainage and infiltration, generating higher runoff. In urban areas, the main drivers of compaction are the stresses imposed by heavy machinery in construction sites and by people trampling in parks/gardens.

For mitigating the disturbance due to heavy machinery in construction sites some guidelines are included in the document “Guidelines for the removal, management and re-use of topsoil at construction sites” that can be retrieved at the following address: <http://www.sos4life.it/documenti/>. In the same document, some guidelines are reported for the re-use of topsoil in new green areas.

All the measures useful for preserve and enhance soil organic matter content and biodiversity have also positive impacts on preventing soil compaction.

Table 5. Relationship between soil bulk density and root growth based on soil texture (NRCS Soil Quality Institute, 1999).shows reference soil bulk density values for different soil textural classes, and their relationships with root growth (NRCS Soil Quality Institute, 1999).

Soil texture	Ideal bulk densities (g/cm ³)	Bulk densities that may affect root growth (g/cm ³)	Bulk densities that restrict root growth (g/ cm ³)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, loams, clay loams	<1.40	1.6	>1.75
Silts, silt loams	<1.30	1.6	>1.75
Silt loams, silty clay loams	<1.10	1.55	>1.65
Sandy clays, silty clays, some clay loams (35-45% clay)	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

Table 5. Relationship between soil bulk density and root growth based on soil texture (NRCS Soil Quality Institute, 1999).

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ANNEX I. PEDOTRANSFER FUNCTIONS

We describe here a set of pedotransfer functions (PTFs) that can be used to estimate the data required for the assessment of the indicators of soil ecosystem services:

- bulk density (Mg m^{-3})
- saturated hydraulic conductivity (mmh^{-1})
- air entry pressure (cm)
- available water capacity (vol./vol.), derivato dal contenuto d'acqua stimato a 333 e 15000 cm di tensione
- cation exchange capacity ($\text{cmol}_c \text{ kg}^{-1}$)

A I.I Bulk density

Soil bulk density is required either as direct input for the calculation of indicators (e.g. soil organic carbon stock, infrastructure support capacity) or as input for the estimation of variables which are in turn required for the calculation of indicators, such as, for example, saturated water conductivity or air entry pressure required to estimate the indicators of water flow regulation in soils.

SR_10	SOIL_REG	Descrizione
A	16.5	Eastern and central Alps on calcareous sedimentary rocks
	34.2	Western Alps on calcareous sedimentary rocks
	34.3	Eastern and central Alps on calcareous sedimentary rocks
	35.6	Western Alps on metamorphic rocks
	37.1	Western and central Alps on igneous and metamorphic rocks
B	37.3	Western Alps on metamorphic rocks
	16.4	Apennine relieves on limestone and intra-mountain plains
	35.7	Highest part of northern Apennine
C	78.2	Northern and central Apennine
	18.7	Langhe, Monferrato and "hills of the Po" on Tertiary marine deposits
	35.4	Hills of Friuli
	67.2	Carso
D	78.1	Hills of Emilia-Romagna and Marche on Tertiary flysch deposits
	18.8	Po plain and moraine hills of Piedmont and Lombardy
E	60.4	Anti-Apennines chains of Tuscany
	61.1	Apennine and anti-Apennines relieves on sedimentary rocks of central and southern Italy
F	66.5	Apennine of Calabria and Sicily on igneous and metamorphic rocks
	59.2	Mountains and hills of Sardinia, on acid crystalline rocks
	66.4	Mountains of Etna
	67.4	Mountains and hills of Sardinia on metamorphic rocks
G	59.1	Hills of Sardinia on basic rocks
	59.7	Hills and mountains on limestone covered by volcanic ashes of southern Italy, and included alluvial and coastal plains
	61.3	Hills of central and southern Italy on Pliocene and Pleistocene marine deposits
H	62.3	Hills of Calabria and Sicily on Tertiary calcareous rocks and sediments, with included alluvial and coastal plains
	72.3	Hills of Gargano
	56.1	Hills of central and southern Italy on effusive volcanic rocks
I	59.8	Hills of Sardinia on basalt and trachyte
	59.9	Hills and mountains on limestone and igneous rocks of Sicily
	62.2	Hills of Sicily on Tertiary clayey flysch, limestone, sandstone and gypsum, and coastal plains
L	72.2	Hills of Murge and Salento
	60.7	Coastal plains of central Italy and included hills
	62.1	Capitanata and plains of Metaponto, Taranto and Brindisi
	64.4	Versilia and internal plains of Tuscany, Umbria and Lazio
	76.1	Campidano and plains of Sulcis and central Sardinia

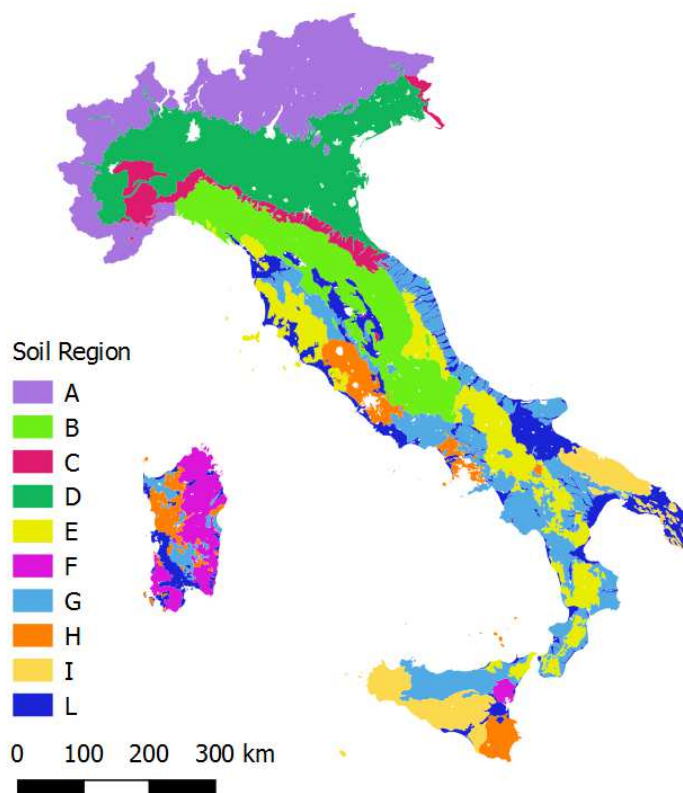


Figure 1. Italian soil regions.

Scientific literature provides a number of PTFs to estimate bulk density. These are calibrated on databases that can be local, regional or continental. In Italy, for examples, PTFs calibrated at regional level are available for Emilia Romagna (Tarocco et al. 2018), Tuscany, and Veneto. More recently, it has been established a database at national level of soil bulk density data ($N = 3043$) to support the realization of the first soil carbon stock map (0-30 cm) of Italian soils. To this goal, PTFs have been calibrated for major land uses (woodlands, pastures and meadows, permanent crops, annual crops) in each of the ten Italian soil regions (Fig. 7), as defined by the Council for Agricultural Research and Economics (CREA-AA). A specific PTF for organic soil horizon has been calibrated as well. The inputs required to estimate bulk density are soil textural fractions (sand, silt, clay, USDA limits) and soil organic carbon %. Particle mean diameter D_g (mm) and its

standard deviation (Sg -) are computed from the three particle size fractions % as follows (Shirazi et al, 1988):

$$Dg = \exp(a), \quad Sg = \exp(b)$$

where

$$a = \sum_{i=1}^n f_i \ln(M_i) \quad \text{e} \quad b = \sqrt{\sum_{i=1}^n f_i (\ln(M_i))^2 - a^2}$$

with n the number of textural fractions, f_i the amount of fraction i^a , and M_i the logarithmic mean of the limit values of the corresponding dimensional range.

The following tables report the algorithms to estimate soil bulk density for the four major land uses in the different Italian soil regions. General linear models (GLM) were used to calibrate the PTFs using the soil regions as categorical predictors.

Soil Region	Intercept	C org	Clay	Dg	Sg	Soil Region
Tutte	1.46823303	-0.07045189	-0.0006427181		-0.00217045	A -0.072846634
						B 0.084066381
						C 0.032496028
						D 0.125400466
						E 0.143919304
						F -0.141780125
						G -0.018292945
						H -0.175243435
						I -0.098264484
						L 0.120545443

Table 1. GLM PTF for bulk density estimation (Mgha-1): annual crops.

Soil Region	Intercept	C org	Ln C org	Clay	Silt	Sand	Dg	Sg	Soil Region
Tutte	1.44443065	-0.07618995			0.0004791				A 0.0912244411
									B 0.0305390199
									C 0.105238663
									D 0.141192449
									E 0.0601010732
									F -0.110013133
									G -0.05491585
									H -0.192832061
									I -0.161653454
									L 0.091118852

Table 2. GLM PTF for bulk density estimation (Mgha-1): permanent crops.

Soil Region	Intercept	C org	Ln C org	Clay	Silt	Sand	Dg	Sg	Soil Region
Tutte	1.2918347	-0.0649351			0.00231335			0.0007366	A -0.1269407950

B 0.0018918827
C 0.1213344180
D 0.1492775290
E 0.0356893461
F -0.3179206830
G 0.0396237258
H 0.0364853163
I -0.073262287
L 0.133821547

Table 8. GLM PTF for bulk density estimation (Mgha-1): permanent meadows and grasslands.

Soil Region	Intercept	C org	Ln C org	Clay	Silt	Sand	Dg	Sg	Soil Region
Tutte	1.216743		-0.16795					0.006818	A -0.263105989
									B -0.005306609
									C
									D 0.0206395292
									E 0.0271433492
									F -0.0224236601
									G -0.056813692
									H 0.1663454444
									I 0.1501642310
									L -0.0166426618

Table 9. GLM PTF for bulk density estimation (Mgha-1): woodlands.

As for organic soil horizons, regardless of land use and soil region, the general relationship between soil organic carbon content and bulk density is the following:

$$\text{Bulk density (Mg m}^{-3}\text{)} = 1.40275788 - 0.338701096 \cdot \text{LN (C org. \%)}$$

Correcting soil bulk density for coarse fragments content

The presence of coarse fragments (diameter > 2mm) often characterize urban soils and, for this reason, it is necessary to correct the PTF estimates of bulk density. The corrected BD values in presence of coarse fragments can be calculated from the BD values for fine earth and coarse fragments (Berger, 1976). In order to calculate the bulk density of the whole soil BD_t , i.e. encompassing fine earth and coarse fragments, we adopt the following equation:

$$BD_t = [(1 - R_m) / BD_f + (R_v / BD_{rf})]^{-1} \quad (1)$$

where R_m is the coarse fragments content on a weight basis; BD_t is the total bulk density (Mg m^{-3}), BD_{rf} is the bulk density of the coarse fragments (reference values are available in literature for different litologies; for example the mean value for the soils of Emilia-Romagna is 2.26 Mg m^{-3}), and BD_f is the bulk density of the fine earth fraction (estimated via PTF).

Generally the available data for coarse fragments is on a volume basis (R_v). The transformation from a volume based to a weight based content is obtained with the following (Torri et al, 1994):

$$R_m = (-BD_{rf} R_v) / (BD_f R_v - BD_{rf} R_v - BD_f) \quad (2)$$

In order to account for the effect of coarse fragments on the bulk density of the fine earth, resulting in an inverse relationship due to the presence of voids and macropores at the interface between coarse fragments and fine earth, it is necessary to resort to the following (Torri et al., 1994):

$$BD_{f_c} = BD_f (1 - 1.67R_m^{3.39}) \quad (3)$$

where BD_{f_c} is the fine earth bulk density in presence of coarse fragments ($Mg\ m^{-3}$); BD_f is again the bulk density of the fine earth estimated via PTF without accounting for the presence of coarse fragments; R_m is the coarse fragments content on a weight basis.

Equation (1) can be written as follows:

$$BD_t = [(1 - (-BD_{rf} R_v) / (BD_f R_v - BD_{rf} R_v - BD_f)) / (BD_f (1 - 1.67R_m^{3.39}) + (R_v / BD_{rf}))]^{-1} \quad (4)$$

Equation (4) is generally used to correct PTF bulk density estimates in soils with more than 10% of coarse fragments.

As for Emilia-Romagna soils, a map of bulk density estimates is available as additional data to the carbon stock map for the plain area of the region, for the interval depth 0-30 cm¹⁰.

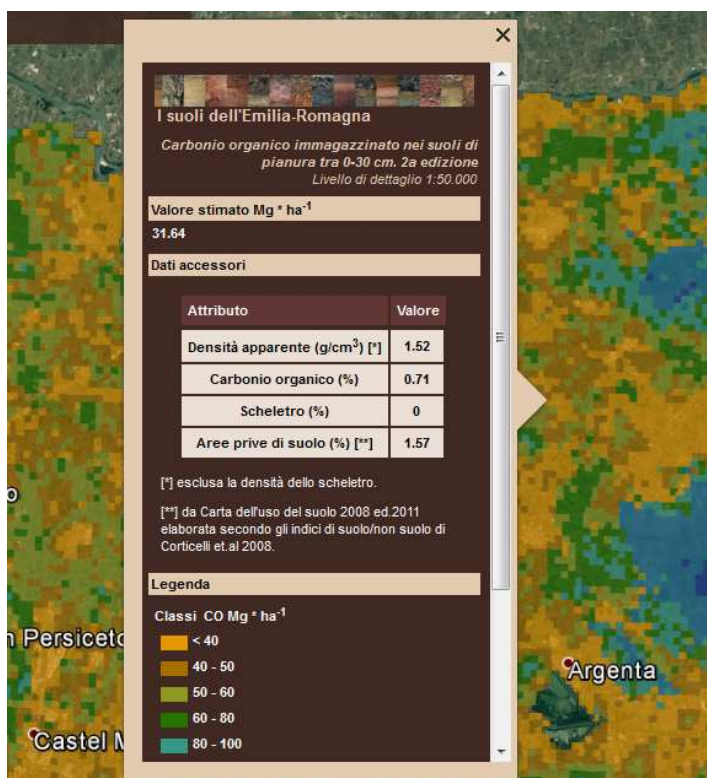


Figure 2. Example of query of the C stock map on the CARTPEDO webpage.

¹⁰ http://mappegis.regione.emilia-romagna.it/gstatico/documenti/dati_pedol/NOTE_ILLUSTRATIVE_stockCO30_pianura.pdf

A I.II Saturated hydraulic conductivity

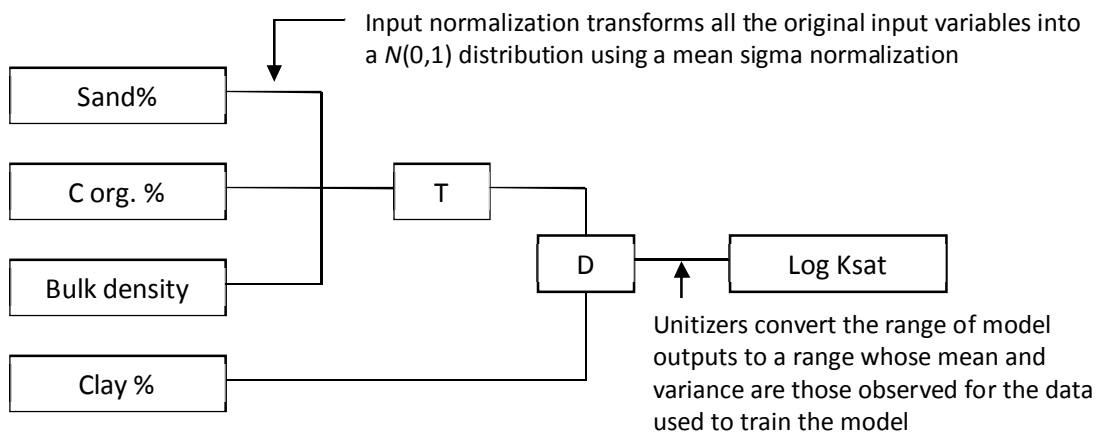
Soil literature provides a number of PTFs to estimate hydraulic conductivity. Among these, one of the most used, and validated with fair accuracy ($R^2 = 0.35$) on an independent dataset for Italian soils ($N = 268$), is the PTF proposed by Brakensiek et al. (1984):

$$K_{sat} \text{ (mm h}^{-1}\text{)} = 10 \cdot \text{EXP} [(19.52348 \cdot \text{PORO}^2) - (8.96847) - (0.028212 \cdot A\%) + (0.00018107 \cdot S\%^2) - (0.0094125 \cdot A\%^2) - (8.395215 \cdot \text{PORO}^2)^2 + (0.077718 \cdot S\% \cdot \text{PORO}^2) - (0.00298 \cdot S\%^2 \cdot \text{PORO}^2) - (0.019492 \cdot A\%^2 \cdot \text{PORO}^2) + (0.0000173 \cdot S\%^2 \cdot A\%) + (0.02733 \cdot A\%^2 \cdot \text{PORO}^2) + (0.001434 \cdot S\%^2 \cdot \text{PORO}^2) - (0.0000035 \cdot A\%^2 \cdot S\%)]$$

where the inputs to the PTF are: sand % (S%), clay % (A%), and porosity (PORO, vol/vol) as estimated from bulk density BD (Mg m^{-3}):

$$\text{PORO} = (1 - \text{BD} / 2.65)$$

On the same dataset of measurements Ungaro et al. (2014) calibrated a PTF resorting to GMDH (Group Method of Data Handling) statistical networks (Ivakhnenko, 1968). The calibrated network has the following structure:



PTF inputs are sand (S%), clay (A%), organic carbon content (CO%) and bulk density (BD, Mg m^{-3} , measured or estimated via PTF, and corrected for coarse fragments). Input variables are normalized prior to being transferred through the network nodes, using the following algorithms:

Normalization input 1

$$A = -1.58807939026797 + 0.043399261792585 \cdot S\%$$

$$B = 0.895704956226224 + 1.90436429623194 \cdot \log(\text{CO}\%)$$

$$C = -6.56853764508901 + 4.86964821073382 \cdot \text{BD}$$

Output first node of the network

$$D = 0.0836015967122676 + 0.416153421876942 \cdot A + 0 \cdot B + -0.445772230372808 \cdot C + -0.134334562427775 \cdot A^2 + -0.0544032825090131 \cdot B^2 + 0 \cdot C^2 + -0.198584356240143 \cdot A \cdot B + 0.096017083549925 \cdot A \cdot C + -0.144971973570487 \cdot B \cdot C + --0.125314845712128 \cdot A \cdot B \cdot C + 0.0716205065345566 \cdot A^3 + -0.123673920290893 \cdot B^3 + 0.0587033757513834 \cdot C^3 + 0.152071065904968 \cdot A^2 \cdot B + -0.102414907323155 \cdot A \cdot B^2 + 0 \cdot A \cdot C^2 + 0 \cdot A^2 \cdot C + -0.156148957009503 \cdot B^2 \cdot C + -0.0305947339564729 \cdot B \cdot C^2$$

Normalization input 2

$$E = -1.65784483580252 + 0.0723996897397788 * A\%$$

Output second node of the network

$$F = 0.174732633027132 + 1.03829358346795 * D + 0.151865200913679 * E + -0.341867233805586 * D^2 + -0.11074767165566 * E^2 + -0.13351716106058 * D * E + -0.461153694809156 * D^3 + 0 * E^3 + -0.367403924274197 * D^2 * E + -0.218709934220076 * D * E^2$$

Final output

$$\text{Log Ksat} = 0.951757462686567 + 1.10472133391165 * F$$

Output check

Validity ranges for estimates are defined as follows:

Range output	Ksat mm/h min	Ksat mm/h max
Fine textured soils	0.0044	24.34
Loamy textured soils	0.93	100.93
Coarse textured soils	7.54	401.79

In case of Ksat estimates falling outside the limit of the calibration range, it is advisable to resort to mean values for USDA textural classes as reported in the following table.

Textural Classes	Mean	Std.Dev.	95% CI lower	95% CI upper	Min.	Median	Max.
C	1.47	2.07	0.04	7.51	0.00	0.78	24.34
CL	11.62	7.85	2.81	32.30	0.93	9.53	75.13
L	12.57	2.61	8.31	18.34	6.80	12.33	25.28
LS	41.87	19.40	14.69	87.23	7.54	37.91	153.95
S	262.88	65.37	142.56	401.79	142.56	256.45	401.79
SCL	30.27	20.93	7.13	100.93	7.13	24.89	100.93
SL	28.80	4.36	21.13	37.96	16.24	28.83	44.62
SiL	5.32	1.46	2.94	8.86	1.48	5.14	12.72
SiC	1.99	1.26	0.43	5.13	0.17	1.69	11.66
SiCL	5.83	3.28	1.42	13.40	0.70	5.15	23.77
All Grps	40.26	78.71	0.32	326.59	0.00	11.25	401.79

Table 3. Ksat (mm h⁻¹): bootstrap statistics for the ten USDA textural classes (N = 1,000). StdDev: standard deviation; 95% CI: 95% confidence interval of the mean. Ksat estimates with the PTF of Brakensiek et al. (1984).

In Emilia-Romagna the map of saturated hydraulic conductivity (Ksat) is available for the plain area of the region¹¹ (Fig. 9).

¹¹http://mappegis.regione.emilia-romagna.it/gstatico/documenti/dati_pedol/ksat_pianura.pdf

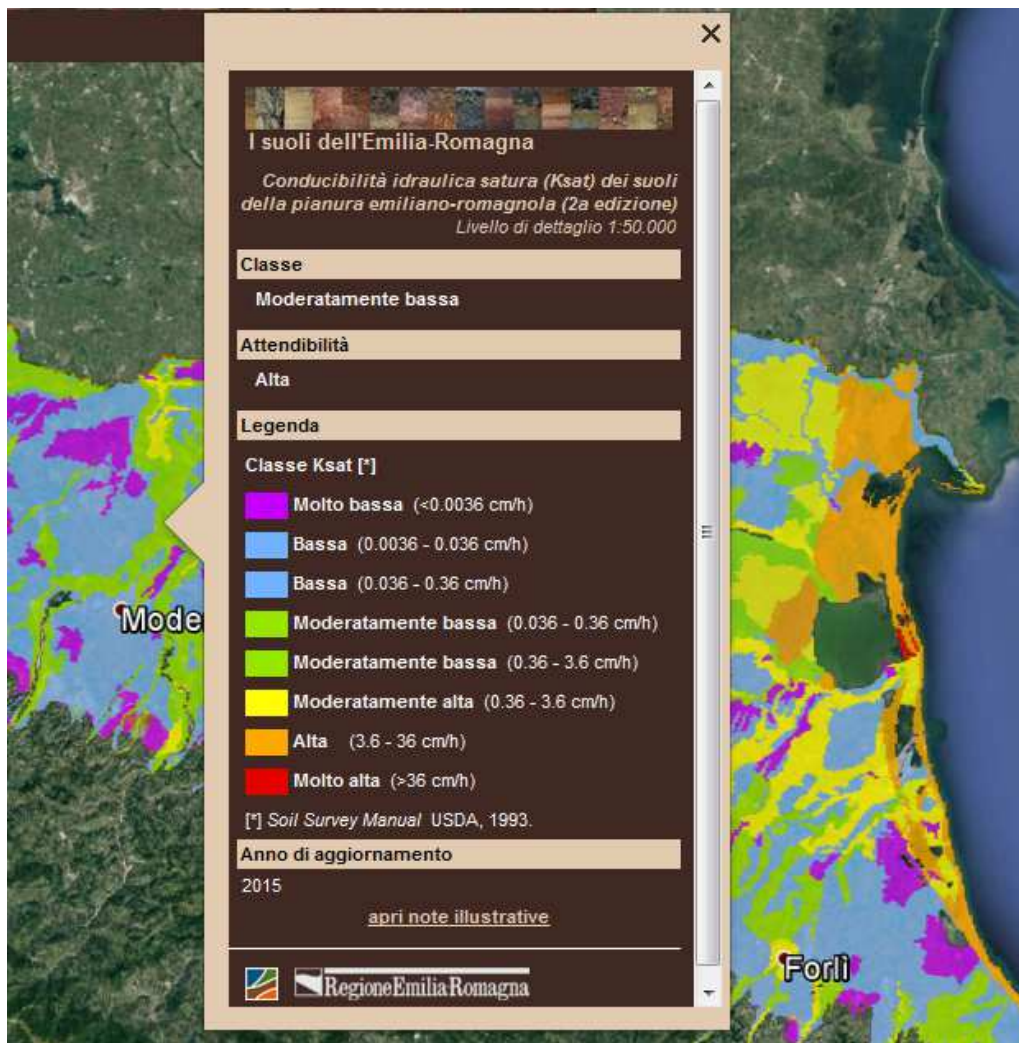
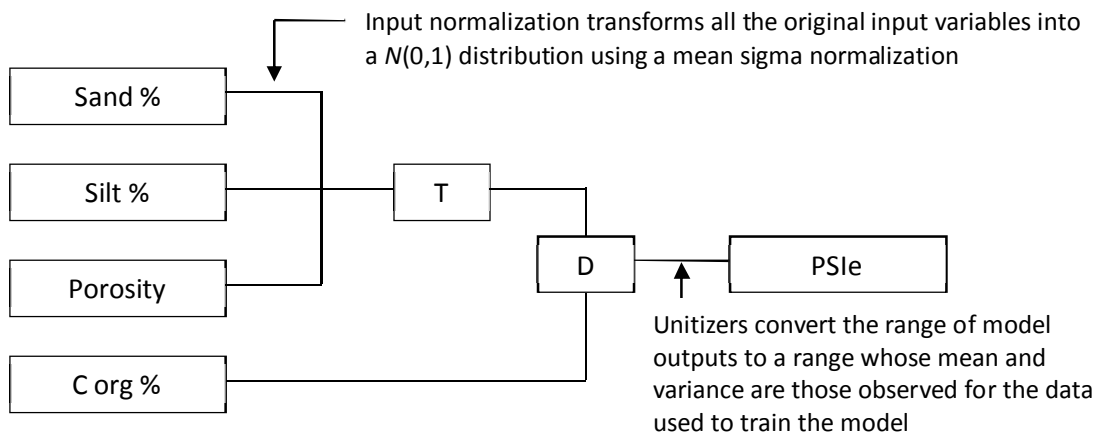


Figure 3. Example of query of the Ksat map on the CARTPEDO web page.

A I.III Air entry pressure

Air entry pressure (PSI_e , cm) corresponds to the matric potential value at which air begins to enter the soil porous system, causing a switch from gravity driven flow (saturation conditions) to capillary flow (unsaturated conditions). Its value is one of the chief factors controlling soil retention properties and determines the inflection point of the soil-water retention curve. For this reason, it compares explicitly in the analytical description of the retention curve in the model proposed by Brooks and Corey (1964) and by van Genuchten (1980). Fine textured soil have high values of air entry pressure ($PSI_e > 100$ cm), while the opposite happens in coarse texture soils ($PSI_e < 20$ cm).

Using a data base of 445 retention curves from Italian soils, Ungaro et al. (2014) calibrated a PTF to estimate $PSI_e >$ using GMDH statistical networks (Ivakhnenko, 1968). The calibrated network has the following structure:



Input PTF: *L%*, *S%*, *CO% (log)*, *PORO1*

S%: sand %

L%: silt %

CO%: carbonio organico % (Log)

PORO1: porosity %, $PORO1 = (1 - (BD / (2.7 * (1 - (Corg\% * 10^{-2}))) + Corg\% * 10^{-2})) * 0.96$

BD: bulk density ($Mg\ m^{-3}$), measured or estimated

Normalization input 1

$$A = -1.55514315777641 + 0.0439626330192209 * S\%$$

$$B = -1.62156839186953 + 0.000826045814054491 * L\%$$

$$C = 5.88501454719847 + 12.6194730338606 * PORO1$$

Output first network node

$$D = -0.568439426027443 + -0.339618598889681 * A + 0.0850629667172664 * B + -0.327793522823292 * C + 1.18970550060609 * A^2 + 0.576355024165541 * B^2 + 0 * C^2 + -0.198584356240143 * A * B + 0.301041218929671 * A * C + -0.10527882324184 * B * C + --0.661480855965559 * A * B * C + 0.151788905416509 * A^3 + 0.133497668914664 * B^3 + -0.0145722698122465 * C^3 + 1.11203822431696 * A^2 * B + 0.964631529651623 * A * B^2 + 0.0684388124744497 * A * C^2 + 0.20749615690423 * A^2 * C + 0.429023990805545 * B^2 * C + 0.0265885830908164 * B * C^2$$

Normalization input 2

$$E = 0.0187145139027159 + 2.11251970495063 * \text{Log}C$$

Output second network node

$$F = 0 + 1.15847606797297 * D + 0.200090177126999 * E + 0.0866162637992406 * D^2 + -0 * E^2 + 0 * D * E + -0.0782508492875681 * D^3 + -0.0274983695657443 * E^3 + --0.0487893822277778 * D^2 * E + -0.0762940081491734 * D * E^2$$

$$PSI_e = 54.443993993994 + 41.7053965834241 * F \quad (MIN=2.658, MAX = 200)$$

A I.IV Available water capacity (AWC)

Available water capacity (Available Water Capacity, AWC) is the maximum amount of water available in a soil that can be used by plants. It is calculated as the difference between the water content at field capacity (field capacity, FC) and the one at wilting point (Wilting point WP). The first is conventionally placed at 333 cm tension (-33 kPa or -33 bar), the second at 15000 cm tension (-1500 kPa or -15 bar). The available water capacity is required for the calculation of the indicator CLI, the water content to the field capacity for the calculation of the indicator WAS.

Using a database of 445 retention curves from Italian soils, Ungaro et al. (2014) calibrated two PTFs to estimate the water content at field capacity and the water content at wilting point. The difference in water content at the two points return the available water capacity.

I.IV.I Water content at 333 cm tension (m³/m³)

Input PTF: *Dg*, *C org %*, *PORO1*, *L%*

Dg: particles size mean diameter

C org%: organic carbon content %

PORO1: estimated saturation %, $PORO1 = (1 - (BD / (2.7 * (1 - (Corg\% * 10^{-2}))) + Corg\% * 10^{-2})) * 0.96$

BD: bulk density (Mg m⁻³), measured or estimated

L%: silt %

Normalization input 1

$A = 3.8102814236164 + 0.827378421952734 * \ln(Dg)$

$B = -0.491141860677084 + 0.367776345566818 * Corg\%$

$C = -5.88752433612624 + 13.0483582639121 * PORO1$

Output first network node

$$D = 0 + -0.47522648155494 * A + 0.407409693528406 * B + 0.101954382069889 * C + 0 * A^2 + 0.286127938068712 * B^2 + -0.103499406792212 * C^2 + 0 * A * B + 0.164039073693382 * A * C + 0.385057943571155 * B * C + 0.302594161247526 * A * B * C + -0.118517243948488 * A^3 + -0.00799822709229998 * B^3 + -0.0474755798398775 * C^3 - 0.259973976218855 * A^2 * B + 0.0279859549205733 * A * B^2 + -0.0932679649932655 * A * C^2 + 0 * A^2 * C + -0.307603329158264 * B^2 * C + 0.267603681660816 * B * C^2$$

Normalization input 2

$E = -1.3033911325751 + 9.74232503307444E-06 * L\%^2$

Output second network node

$$F = 0 + 0.99590304675235 * D + 0.0852214730608352 * E + 0 * D^2 + 0 * E^2 + 0 * D * E + 0 * D^3 + -0.0297749925104875 * E^3 + 0 * D^2 * E + 0 * D * E^2$$

$CI_{333} = 0.34296644295302 + 0.0984845588190126 * F$ (MAX= 0.671, MIN= 0.064)

I.VI.II Water content at 15000 cm tension (m^3/m^3)

Input PTF: *Dg*, *C org %*, *BD*

Dg : particles size mean diameter

C org% : organic carbon content %

BD: bulk density ($Mg m^{-3}$), measured or estimated

The estimation algorithm has the following structure:

Normalization input 1

$$A = 3.77140361228726 + 0.819740344988767 * \ln(Dg)$$

$$B = -0.49157638336218 + 0.367695186350225 * Corg\%$$

$$C = -2.905574766004 + 0.947767333204745 * BD^3$$

Output first network node

$$D = 0 + -0.763103574848119 * A + 0.236868672084561 * B + 0. -0.0731674247644929 * C + 0 * A^2 + -0.434887427284714 * B^2 + -0.105886229669014 * C^2 + 0.302936372100644 * A * B + 0 * A * C + -0.483229853413334 * B * C + 0.0494789265032567 * A * B * C + 0 * A^3 + -0.164404279418551 * B^3 + 0.0589897728741078 * C^3 + -0.221540878505337 * A^2 * B + 0.241483606228241 * A * B^2 + 0 * A * C^2 + 0 * A^2 * C + -0.334515879151902 * B^2 * C + 0.150148733944991 * B * C^2$$

$$CI_{15000} = 0.236463087248322 + 0.104480408320589 * D \quad (\text{MAX. } 0.546; \text{MIN. } 0.012)$$

A I.V Cation exchange capacity

The cation exchange capacity (CSC, $cmol kg^{-1}$) is required for the calculation of the indicator BUF. In the absence of measured values, the CSC can be estimated by using pedotransfer functions. Several PTFs have been calibrated to estimate CSC from physico-chemical properties (Breeuwsma et al., 1986; Manrique et al., 1991; Bell and Van Keulen, 1995; McBratney et al., 2002); in most cases these models are based on a linear relationship between CSC, organic matter (or organic carbon) content, and clay content. Calzolari et al. (2016) calibrated the following report on a database of 3269 observations from Italian soil:

$$CEC (cmol kg^{-1}) = 6.332 + 0.404 Clay \% + 1.690 C org \% \quad (R^2 = 0.75)$$

A I.VI References

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ANNEX II. SOIL ECOSYSTEM SERVICES ASSESSMENT

Depending on available data, soil ecosystem services assessment can follow three different approaches:

1. Being based on data derived from *ad hoc* urban soils survey;
2. Being based on available soil maps and data from benchmark soil profiles;
3. Being based on available thematic maps derived from soil maps or other soil information in raster or vector format (tiles).

A II.I Assessment based on *ad hoc* soil survey

This case has been briefly described in paragraph 2.2.1 and more in details in the deliverable of action B 1.3 (<http://www.sos4life.it/documenti/>). It requires good processing capacity, as the necessary thematic layers (soil textural fractions, pH, organic carbon) should be derived from the analyzed data, following the urban soil survey. The soil capability map can be derived from local data or from already available maps.

The derivation of thematic maps from soil data is beyond this discussion and it is necessary to refer to the Digital Soil Mapping techniques. Examples of this type of technique can be found in numerous publications (Ballabio et al, 2016; Boettinger et al, 2010; Dobos et al, 2010; Hengl et al, 2014; Lagacherie et al, 2006; McBratney et al, 2003; Orgiazzi et al., 2018; Scull et al., 2003). As an alternative to digital soil mapping techniques, the analyzed data can be used to calculate the indicators for the different land uses found in urban soils (e.g. parks, roundabouts, private green areas, sports green areas, agricultural areas).

A II.II Assessment based on available soil maps and benchmark soil profiles

This method was used in the SOS4LIFE project to draw up the soil ecosystem services maps of the municipalities of Forlì and San Lazzaro di Savena. In the case of the Emilia-Romagna region, the 1: 50,000 soil map (available for 71% of the territory) is accompanied by local chemical-physical analyzes for each soil profile present in the map polygons (unambiguously described). In the case of other regions, it is instead necessary to refer to the analyzes that accompany the benchmark profile of each soil described in the map and to process the data in terms of map units (i.e. groups of polygons with similar soils).

The methods of calculation using this method have been described in the document "Local representative sites of the soils of the plain, the lower and middle Apennines of Emilia-Romagna" (Tarocco et al, 2018). The document also indicates how to download the data.

The input data necessary for the assessment are:

- Soil map;
- Analysis of reference soil profile (skeleton, textural fractions, organic C %);
- Soil capability map;
- Map of the average depth of the shallow water table (in the case of lowland areas).

A II.III Assessment based on thematic maps in raster or vector tiles format

With this assessment method the soil map is not strictly necessary. This method was used to calculate the SEs of the Emilia-Romagna plain (Calzolari et al, 2016), but it can be implemented at local scale if the information is sufficiently detailed. In the case of the Emilia-Romagna region, the necessary thematic maps (with the exception of pH) are available in the plain area in vector format with cells of 500 m x500 m. This makes the final maps more detailed than the previous method. The data can be downloaded directly from the Geocatalogue. The level of detail available in the other regions is very variable.

The necessary input data are:

- texture and skeleton map (topsoil and subsoil);
- map of organic carbon content (topsoil and subsoil);
- map of organic carbon stock (topsoil and subsoil): this layer can be derived from the two previous maps;
- pH map (topsoil and subsoil);

- soil capability map;
- map of the average depth of the shallow water table (in the case of lowland areas).

A II.IV References

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ANNEX III. DEFINITION AND ASSESSMENT OF THE QBS-ar INDEX

Soil animals have different degrees of adaptation to hypogean life. They display specific adaptation features such as: the absence of visual organs, the lengthening and flattening of the body, the shortening of the sensory and locomotor appendages, the reduction or disappearance of some appendages (such as the furca, a organ used for jumping in *Collembola*, or metathoracic wings in *Coleoptera*), the presence of sensory organs to detect the degree of humidity, depigmentation or crypto-pigmentation to merge with soil particles as in mites, reduction or disappearance of sensory organs that absorb light radiation (Menta, 2012). The various groups are defined by biological forms characterized by the same series of convergent characters. These organisms have therefore adapted to the soil edaphic environment and can no longer survive outside it (Parisi et al., 2005).

Micro-arthropods play an important role in the trophic chain and energy flow that accompanies the last phases of the organic matter cycle. They are involved in the crushing of plant residues, in the demolition and translocation of organic matter, in the control and dispersion of micro-flora and micro-fauna, and are predators of micro- and the meso-fauna (Menta, 2012). We can therefore consider them good bio-indicators. The degree of adaptation of the biological forms to life in the soil varies according to the presence and combination of the characters mentioned above. Its quantification uses a scale of reference scores called EMI (EcoMorphological Indexes). For each character indicating adaptation to the soil environment, a score is assigned, from a minimum of 1 to a maximum of 20, depending on whether the morphological features are weakly or strongly adapted to the soil environment. Therefore, in QBS-ar there is not so much reference to taxonomy, but rather to the degree of adaptation to the soil environment and to evolutionary convergence. For the features that indicate the greatest degree of adaptation to soil conditions an EMI score of 20 is assigned (edaphic), while a score of 1 (epi-edaphic) is assigned to slightly adaptation features. All biological forms characterized by intermediate conditions have a score equal to their degree of specialization (emi-edaphic). Table 11 provides a list of EMI scores.

Group	Order	EMI score
Epi-edaphic	<i>Dermaptera, Psocoptera, Thysanoptera, Other holometaboluos insects (adults)</i>	1
	<i>Hymenopera, Araneae</i>	1-5
	<i>Orthoptera, Emiptera</i>	1-10
Emi-edaphic	<i>Collembola, Coleoptera</i>	1-20
	<i>Blattaria</i>	5
Edaphic	<i>Embioptra, Diptera (larvae), Other holometaboluos insects (larvae), Opiliones, Isopoda</i>	10
	<i>Chilopoda, Diplopoda</i>	10-20
	<i>Protura, Diplura, Acari, Palpigradi, Pseudoscorpiones, Pauropoda, Symphyla</i>	20

Table 4. EMI scores for soil per micro-arthropods (Parisi, 2001).

When in a soil sample there are different biological forms belonging to the same group, only the highest EMI value (maximum EMI) is taken into account. The biological soil quality index (QBS-ar) is a total score attributed to a soil sample and is given by the sum of all the individual EMI scores. The application of the QBS-ar method is divided into 5 five steps: i) sample collection, ii-iii) extraction and conservation of micro-arthropods, iv) determination of the biological forms contained and finally v) calculation of the QBS-ar index.

In the absence of direct measures, land use can be used (e.g. CORINE Land Cover, 4th level), attributing average QBS-ar values based on land use classes based on data from literature (Menta et al., 2008) :

- High (QBS-ar, 150-250) for permanent meadows and pastures, woodlands and peat bogs;
- Medium (QBS-ar, 100-150) for agricultural lands in rotation with meadows and minimum tillage;
- Low (QBS-ar, 60-100) for other land uses.

The indicator proposed as a proxy for the estimation of soil biodiversity (BIO) also takes into consideration the organic C content and bulk density, and has the following form:

$$BIO_{0-1} = (\text{LogOC}_{0-1} - BD_{0-1}) + \text{QBSar}_{0-1}$$

with QBSar_{0-1} equal to 1, 0.5 and 0.25 respectively for high, medium and low biodiversity depending on the prevalent land use.

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