Geoderma 261 (2016) 190–203

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

A methodological framework to assess the multiple contributions of soils to ecosystem services delivery at regional scale

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form 13 July 2015
Accepted 21 July 2015
Available online xxxx

Keywords:
Ecosystem services
Soil properties and functions
Pedotransfer functions
Soil quality indicators

ABSTRACT

Methodologies used for identifying, assessing and mapping ecosystem services are diverse and frequently inconsistent and notwithstanding the examples from available literature evident methodological gaps are still present. This paper presents an indicator based approach to assessing and mapping the multiple contributions of soil to the delivery of ecosystem services, based on soil functions as derived from available soil data for a reference depth of 100 cm. Of operational value is the fact that, within this framework, several functions can be treated and mapped simultaneously, providing an efficient tool to model the heterogeneity of different soil functions, both at local and regional scale. The methodology consists of: (i) definition of soil based eco-system services, based on available and derived soil data and on societal demands; (ii) definition of appropriate indicators for the functions underpinning the services and coding; and (iii) assessment and mapping of soil potential contribution to multiple ecosystem services. In this paper, we used spatial data to characterise and model the spatial heterogeneity of soil functions in the case study area of alluvial plain of Emilia Romagna (Northern Italy). In order to explicitly take into account the spatial variability of soil properties and the related uncertainty, and in order to exploit at best the available information, we: (i) realised a continuous coverage of basic soil properties via geostatistical simulations conditional on available 1:50,000 soil map and land use map, and (ii) derived the necessary soil properties via locally calibrated pedotransfer functions and using other available information, such as land capability map. Results provide new insights about the composition and interrelation of multiple soil functions and potential services in the region and highlight the difference between soils in term of joint functions provision.

1. Introduction

The need for an inter- and trans-disciplinary approach to present, and eventually future, global environmental challenges has been stressed in numerous papers in recent years (Bouma, 2014; Bouma and McBratney, 2013), calling for a proactive involvement of soil scientists in addressing complex issues and societal demands. Most of the global environmental sustainability issues of today, such as food, water and energy security, climate change, and biodiversity protection require that the knowledge acquired in the last few decades by soil science is fully exploited and shared with all the other relevant disciplines (McBratney et al., 2014). Soil provides multiple and multifaceted functions: food production, source of raw material, seat of human activities, historical archive, biodiversity pool, organic carbon sink, and water and nutrients cycle regulator. This holistic concept is strictly linked to the concept of soil quality, defined by Doran and Parkin (1994) as "the capacity of a soil to function, within ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health". Even if the recognition of the multi-functionality of soil was already present in the Doran and Parkin (1994) definition of soil quality, the difficulty of finding indicators able to describe this complexity remains a critical issue (Brevik, 2009; Karlen et al., 1997; Olarieta et al., 2011). The recently framed Millenium Ecosystem Assessment (MEA) (2005) provides a general framework for describing ecosystem services, defined as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly" (De Groot et al., 2002), or "benefits people obtain from ecosystems" (MEA, 2005). Four categories of ecosystem services are distinguished, these being: supporting, provisioning, regulating and cultural services.

Even if the original framework does not explicitly recognize the role of soils as providers of ecosystem services (or disservices), several soil scientists are now filling this gap, linking the concepts of soil natural capital, soil functions, and services soils provide (e.g., Bouma, 2014; Dominati et al., 2010; Hewitt et al., 2015; Palm et al., 2007; Robinson et al., 2009,

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http://dx.doi.org/10.1016/j.geoderma.2015.07.013
0016-7061/

2012; McBratney et al., 2014). The soil natural capital, represented by soil properties (Dominati et al., 2010), or by the stock of mass and energy, and their organization (Robinson et al., 2009), is part of the environmental assets (Costanza et al., 1987) and through its multiple functions contributes to the four categories of ecosystem services: (1) supporting: providing support for plants (and nutrient delivery) and human activities; (2) regulating: through hydrological and biogeochemical (included carbon) cycles centred in soil together with its buffering capacity, e.g. for sustainable waste disposal; (3) provisioning: as a source of raw materials and with biomass production; and (4) cultural: as an archive of archaeological heritage and as a fundamental part of landscapes (Dominati et al., 2010; Robinson et al., 2009). Moving from theoretical frameworks to operational approaches is however still a challenge, for a number of issues. First, the multiplicity of soil functions and the related ecosystem services has as counterpart the multiple expectations and perceptions of the various soil users, and, even if there is an increasing interest in economically quantifying the soil services (Malucelli et al., 2014), there are still some of them that are difficult to monetise, such as those related to public health, water quality, spiritual and cultural heritage, education. This can lead to conflicts and contradictions when land planning policies take place. Then, as soil based ecosystem services co-occur in space and overlap interacting at different spatial and temporal scales, their spatial distribution, synergies and trade-offs play a relevant role in the process of land planning. Finally, scales of application can span from national soil cover to local soil bodies and data availability can be limited. It is therefore of pivotal importance to account explicitly for soil spatial distribution (van Wijnen et al., 2012) in order to characterise the multifunctional attributes of soils in a given area and to preserve their natural capital (Haygarth and Ritz, 2009).

This paper presents a methodological framework to assess the contribution of soil functions to potential ecosystem services (ES) provision at regional scale for the plain area of the Emilia-Romagna region (North East Italy).

The adoption of an ES framework would require the modelling of interactions between soil functions and external drivers (e.g. land use and management, and climate). Here we focus on the performance of soil functions based on soil properties regardless of external drivers, aiming at a multiple objective based land evaluation. This would constitute the first step of a comprehensive ES mapping exercise.

According to the Regional Act 20/2000 about the use and protection of soil, land and soil conservation issues are emphasised. Nonetheless, due to several reasons, soils are still threatened by a high rate of sealing (about 8% of the whole region and about 14% of the plain areas in 2008). The approach is spatially explicit and is based on a set of indicators of soil functions inferred from a set of georeferenced soil characteristics and properties in a intensively cultivated area in northern Italy. The connections between specific soil characteristics and properties and the resulting functions are made explicit via a set of locally calibrated and literature pedotransfer functions (PTFs). The approach incorporates the local understanding of soils geography and land use, and via PTFs links soil processes and properties contributing to ES delivery to a standardised estimation of each soil function.

The identification of multiple soil function areas and the understanding of their spatial patterns and connectivity can provide a further strong basis to support land planning and management.

2. Material and methods

2.1. Study area

Emilia Romagna (lat 43°50′N–45°00′N; long 9°20′E–12°40′E Greenwich, approx.) is situated in Northern Italy and has a total area of 22,124 km^2. The main agricultural area, covering slightly more than half of the region (~12,002 km^2), is the continuous plain stretching south of the Po river and delimited by the Apennines range in the south and by the Adriatic sea in the east. The soils of the Emilia Romagna Plain sustain intensive agricultural activities, which range, according with local climatic conditions, from typical continental productions such as grasslands and dairy farms, cereals and pig farms in the west, to Mediterranean crops (orchards, vineyards, vegetables) and cereals in the east.

Soil data are routinely collected and analysed by the Regional Soil Survey and by Agricultural Extension Services. At present about 3302 soil profiles (17,652 soil horizons) over 10,734 km^2 of cultivated land are identified by a complete set of physical and chemical parameters. For each site the textural fractions (%, USDA, 1993) and soil organic carbon content (%, modified Walkley–Black method; Nelson and Sommers, 1982) are available for a reference depth of 100 cm. These sites are linked to a regional catalogue of 237 soil typological units (STUs) mapped in the available 1:50,000 soil map of the plain (Regione Emilia Romagna, 2006). Textural fractions and soil organic carbon content were spatialised over a 1 km regular grid (N = 11,453) via sequential Gaussian simulations using a scorpan kriging approach (McBratney et al., 2003) conditional on soil map delineations and land use; the resulting maps have been validated for textural fractions and organic carbon content (Ungaro et al., 2010), which represent the main inputs of a set of locally validated pedotransfer functions for estimating soil bulk density and water retention properties (Ungaro et al., 2005) and for hydraulic saturated conductivity (Rawls and Brakensiek, 1989). Descriptive statistics of the data used to define the indicators of the potential contribution of soil to ecosystem services supply are summarised in Table 1.

For post processing of results in terms of contribution to the potential supply of soil based ecosystem services at regional scale, functionally distinct pedo-landascapes (Table 2) based on the 1:500,000 Soil Map of the Emilia Romagna region (Regione Emilia Romagna, 2013) were considered; the pedo-landscape map, encompassing 14 pedo-landscape units, is showed in Fig. 1.

2.2. Soil properties, functions and services

In this study eight soil functions, underpinning the potential delivery of ecosystem services, were considered and assessed with a different level of approximation, based on existing soil data and related research. Among the multiple soil functions we considered the: 1) habitat for soil organisms (BIO); 2) filtering and buffering (BUF); 3) contribution to microclimate regulation (CLI); 4) carbon sequestration potential (CSP); 5) food provision (PRO); 6) support to human infrastructures (SUP); 7) water regulation (WAR) and 8) water storage (WAS). The proxies adopted to infer the functions are summarised in Table 3.

The selected soil functions were described through indicators based on soil properties. Indicators were chosen based on available literature, as described in the following paragraphs. The necessary input data were mapped over a 1 km ∗ 1 km regular grid, for a total of 11,943 grid cells. The calculation results for each indicator at each grid cell were standardised as numbers in the range 0 to 1 (Wu et al., 2013) resorting to an interval normalization as follows:

$$X_i' = (X_i - X_{min})/(X_{max} - X_{min}) \tag{1}$$

where X_i' is the standardised [0–1] value, X_i is the actual value, X_{min} and X_{max} are the maximum and the minimum respectively of each considered variable in the dataset. The formula in Eq. (1) gives high priority (i.e. values close to 1) to higher values of the considered indicator; the lowest value, 0, does not indicate that the function is not provided, but that it is the lowest in the considered area.

2.2.1. Habitat for soil organisms

Soil organisms provide important ecosystem services (Jeffery et al., 2010). These include the storing and cycling of nutrients and pollutants, the decomposition and cycling of soil organic matter, the biocontrol of pests. Among soil organisms, soil micro fauna has been used as indicator

Table 1
Basic and derived soil properties used for the definition of eight indicators of soil functions (N = 11,453). Skel.: coarse fragments; CEC: cation exchange capacity; PSI_e: air entry potential; K_{sat}: saturated hydraulic conductivity: WC_{33}: volumetric soil water content at −33 kPa tension; WC_{1500}: volumetric soil water content at −1500 kPa tension; AWC: available water capacity: WT: shallow water table depth.

Variable	Unit	Mean	Std. Dev.	Minimum	Median	Maximum	Skewness	Kurtosis
Sand	%	26.72	16.47	0.03	23.23	97.70	1.79	4.25
Silt	%	43.84	11.02	0.19	45.11	85.20	−1.15	2.52
Clay	%	29.44	11.30	0.11	27.84	76.08	0.39	0.35
Skel	%	0.01	0.05	0.00	0.00	0.31	5.91	33.55
Organic carbon	%	1.44	2.64	0.07	0.83	30.10	4.73	22.97
Bulk density	$Mg\ m^{-3}$	1.51	0.10	0.59	1.54	1.67	−3.82	17.18
Carbon stock	$Mg\ ha^{-1}$	61.96	35.33	0.00	55.17	517.88	5.53	37.43
CEC	$cmol\ kg^{-1}$	20.64	6.23	6.92	19.57	65.87	1.27	3.37
PSI_e	cm	65.75	29.29	10.27	62.65	148.01	0.55	−0.29
K_{sat}	$mm\ h^{-1}$	11.43	0.47	0.00	824.04	45.01	5.46	36.92
WC_{33}	$vol\ vol^{-1}$	0.35	0.09	0.06	0.34	0.67	1.12	5.80
WC_{1500}	$vol\ vol^{-1}$	0.24	0.07	0.00	0.24	0.55	−0.11	2.44
AWC	$mm\ m^{-1}$	160.07	71.26	18.80	147.15	711.78	3.82	17.47
WT	cm	159.38	27.54	83.64	158.04	249.23	0.38	0.09

of soil quality; its role includes litter fragmentation, macropores formation, bioturbation. In particular, the presence and diversity of soil microarthropods has been recently used in several works (Gardi et al., 2008; Menta et al., 2008; Parisi et al., 2005; Yan et al., 2012). The QBS index ("*Qualità Biologica del Suolo*"), developed in Italy (Parisi, 2001; Parisi et al., 2005) as an index for assessing the biological quality of soil, is based on the number of microarthropod groups adapted to the soil habitat. The underlying concept is that the higher the soil quality, the higher the number of microarthropod groups (*ar*) adapted to the soil habitat, the higher the QBS_{ar} (Parisi et al., 2005). QBS has been widely used in Italy, for characterising the impact of different land use systems on biological soil quality (Gardi et al., 2006, 2008; Menta et al., 2008, 2011). Moreover, its sensitivity, stability and repeatability have been assessed on soils of Po river valley (Aspetti et al., 2010). According to these studies, it resulted sensitive to seasonal climatic variations (Aspetti et al., 2010), and agriculture management intensity (Menta and Leoni, 2008). QBS resulted significantly correlated to the Shannon–Weiner (H') diversity index (Blasi et al., 2013; Galli et al., 2014) and taking into account the whole soil microarthropod community, can be considered a proxy for soil biodiversity (Aspetti et al., 2010). Due to its versatility and relative simplicity (Turbé et al., 2010), QBS_{ar} index is becoming popular in Italy (Aspetti et al., 2010) and widely adopted by national and regional Environmental Protection Agencies (e.g. ARPA Piemonte, 2002; ARPAV, 2014; Menta and Leoni, 2008; Nappi and Jacomini, 2004). In our approach, the qualitative ranking of QBS_{ar} was used as proxy for the calculation of the *Potential habitat for soil organisms indicator* (BIO). Based on literature data (Menta et al., 2008), three qualitative classes were defined, for QBS_{ar} linked to land use: High (QBS_{ar}, 150–250), for permanent grasslands, peat areas and woods; Medium (QBS_{ar}, 100–150) for arables where rotations with grassland is practiced and for no tilled orchards; and Low (QBS_{ar}, 60–100) for other land uses. QBS_{ar} in urban areas was classed as 0 (Prokop et al., 2011). Land use data were derived from the Land Use Map of Emilia-Romagna, 1:25,000 scale (Regione Emilia Romagna, 2011), and integrated with data from the 2010 general agriculture census (Istat, 2010) and soil properties. Considering only the inherent soil properties, it is likely that soils rich in organic matter and not compacted are potentially capable to host a relatively higher biodiversity pool (Gardi et al., 2013). As indicator of the potential of soil in preserving soil biodiversity, BIO, we then considered the log-transformed soil bulk density (BD, $m^3\ m^{-3}$) and log-transformed soil organic matter content (OC, %) for topsoil (0–30 cm), combined with the ranked QBS_{ar} (High = 1; Medium = 0.5; Low = 0.25) as follows:

$$BIO_{0\text{–}1} = (\mathrm{Log}\,OC_{0\text{–}1} - BD_{0\text{–}1}) + QBS_{ar\,0-1}. \quad (2)$$

Table 2
Description and area extent of the 14 pedolandscape units of the Emilia Romagna plain.

Pedolandscape unit	Area, km^2 (share%)	Description
A1	555 (4.8%)	Coarse textured soils on coastal plain
A2	473 (4.1%)	Fine textured soils, with organic layers and peat on recently reclaimed area of Po river delta plain
A3	583 (5.1%)	Loamy textured soils on meander plain of Po river
A4	357 (3.1%)	Fine textured soils on the ancient depressions of Po river delta plain
A4c	856 (7.5%)	Fine to loamy textured soils on the levee areas of the alluvial plain of the delta plain of Po river
A5a	2992 (26.1%)	Loamy textured soils on the levee areas of the Apennines recent alluvial plain
A5b	847 (7.4%)	Loamy textured soils on the levee areas of the Apennines ancient alluvial plain
A6a	1249 (10.9%)	Fine textured soils on the former depressions of the Apennines recent alluvial plain
A6b	254 (2.2%)	Fine textured soils on the former depressions of the Apennines ancient alluvial plain
A7a	718 (6.3%)	Loamy textured soils with presence of rock fragments on recent terraced areas of Apennines rivers
A8	915 (8.0%)	Loamy textured soils with rock fragments at variable depth on alluvial fans of Apennines
A8c	714 (6.2%)	Fine to moderately fine textured soils with strongly differentiated profile on alluvial fans of Apennines
A9a	291 (2.5%)	Loamy skeletal soils with strongly differentiated profile on alluvial gravelly terraced fans
A10	641 (5.6%)	Moderately fine to fine textured soils with strongly differentiated profile, on the Apennine margin

2.2.2. Filtering and buffering

As indicator for the natural attenuation capacity of soils (BUF), we based on the scheme for assessing the natural attenuation capacity of soils used by the Soil Survey of Emilia-Romagna (Regione Emilia Romagna, 1995). This scheme considers soil cation exchange capacity, CEC (<10 cmol kg^{-1} or >10 cmol kg^{-1}) and pH (<6.5, >6.5) of the ploughed horizon, rooting soil depth (>100 cm, <100 cm), and coarse fragment content (>35%, <35%) within the first 100 cm. This must be considered as a rough proxy for natural attenuation capacity, as the soil biological activity is not considered. In order to have a continuous spatial coverage of CEC values over the whole plain, CEC of soils (cmol kg^{-1}) was calculated from soil properties gridded values using a locally calibrated PTF based on available clay and organic matter contents (N = 3269):

$$CEC = 6.332 + 0.404\,Clay + 1.690\,C\,org\left(R^2 = 0.75\right). \quad (3)$$

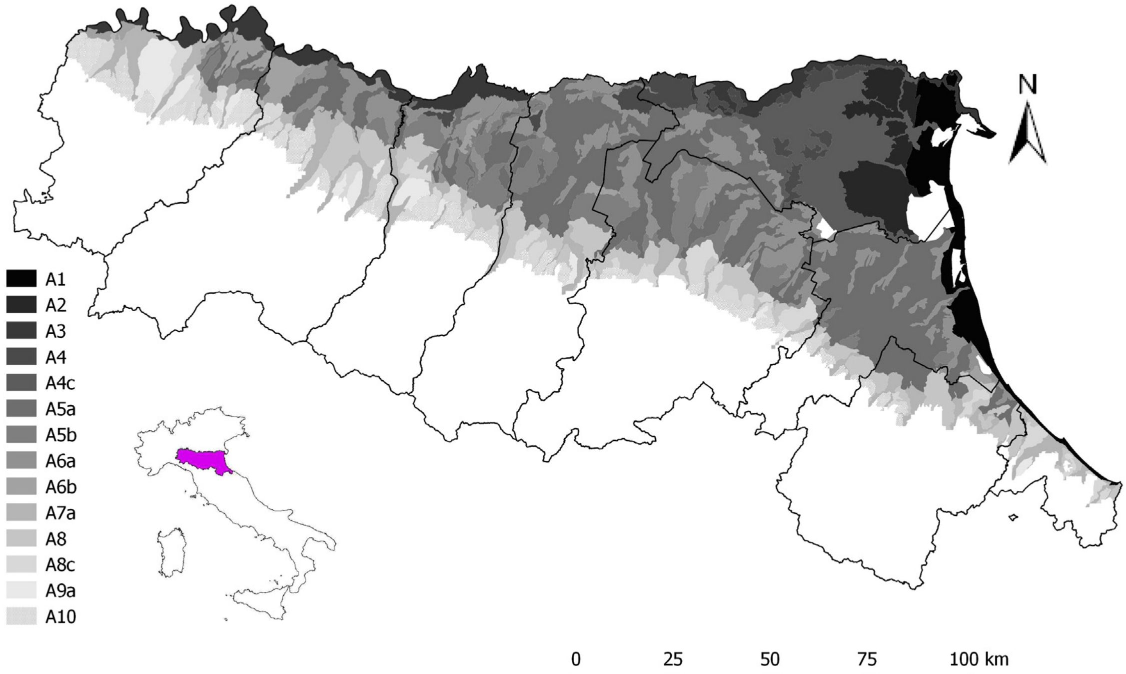

Fig. 1. Pedolandscape map of the Emilia-Romagna plain (Regione Emilia Romagna, 2012, mod.). A1: coarse textured soils of coastal plain; A2: Fine textured soils of the recently reclaimed areas of the Po river delta plain, with organic layers and peat; A3: Loamy textured soils of the meander plain of Po river; A4: Fine textured soils of the ancient depressions of Po river delta plain; A4c: Fine to loamy textured soils of the levee areas of the alluvial plain of the delta plain of Po river; A5a: Loamy textured soils of the levee areas of the Apennines recent alluvial plain; A5b: Loamy textured soils of the levee areas of the Apennines ancient alluvial plain; A6a: fine textured soils of the former depressions of the Apennines recent alluvial plain; A6b: fine textured soils of the former depressions of the Apennines ancient alluvial plain; A7a: Loamy textured soils of recent terraced areas of Apennines rivers, with presence of rock fragments; A8: Loamy textured soils of alluvial fans of Apennines, with rock fragments at variable depth; A8c: Fine to moderately fine textured soils of alluvial fans of Apennines, with strongly differentiated profile; A9a: Loamy skeletal soils of alluvial gravelly terraced fans, with highly differentiated profile; A10: Moderately fine to fine textured soils of the Apennine margin, with strongly differentiated profile.

In order to deal with the asymmetry of the distribution (skewness 1.27), the values of CEC were log-transformed.and then standardised to the range [0,1].

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

Table 3
Ecosystem services (ESs), underpinning soil functions and indicators.

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 potential	Organic C and bulk density (0–30 cm)	CSP
Provisioning	Food provision (potential)	Biomass production	Land capability (LC) map	LC classes and intergrades	PRO
Provisioning (supporting)	Supporting human activities and infrastructures (potential)	Physical and cultural environment	Soil bearing capacity	Sand content Clay content Hydraulic saturated conductivity Peat presence	SUP
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

[a] MAE, 2005.
[b] Dominati et al., 2010.
[c] CEC, 2006.

was taken into account for decreasing the overall attenuation capacity of the soil. This information was derived by the long term average of the shallow water table available for the plains of Emilia Romagna (Barca et al., 2013; Calzolari and Ungaro, 2012). In case of soils with pH values lower than 6.5 (first 30 cm), the natural attenuation capacity index was reduced by 0.25 in case of low CEC soils and by 0.5 in case of high CEC soils (>10 cmol kg^{-1}), according to the local scheme. In case of soils with coarse fragments (i.e. skeleton >30% to a reference depth of 100 cm), the natural attenuation capacity index was reduced by 0.25. BUF_{0-1} was then calculated as:

$$BUF_{0-1} = \mathrm{Log}\,CSC\,(pH, sk)_{0-1} \quad (4)$$

for water table deeper than 100 cm, and

$$BUF_{0-1} = \mathrm{Log}\,CSC(pH, sk)_{0-1} * (WT/100) \quad (5)$$

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).

2.2.3. Local (micro)climate regulation

Ecosystems regulate global and local climate, being sources or sink of greenhouse gases (GHGs), influencing albedo and regulating evapotranspiration (Smith et al., 2013). Locally, vegetation influences microclimate, in particular in urban environments, by providing shadowing and regulating temperature and humidity. Beside influencing the water cycle, evapotranspiration is linearly linked with latent heat, which means that the higher the evapotranspiration, the more energy is used for converting water from the liquid to the gas phase, and the less energy is available in form of sensible heat, which plays an important role in affecting the air temperature (Schwarz et al., 2011).

As indicator of the soil contribution to local (micro)climate regulation (CLI) we chose the potential soil answer to evapotranspiration demand. This indicator was assessed by considering the log transformed available water capacity of soils (AWC) to a reference depth of 100 cm. In this case the occurrence of a shallow water table within the first 300 cm from the field surface was also included in the calculation of the indicator considering its average depth (WT, cm), taking into account its potential contribution to soil evaporation, and eventually to microclimate regulation. The contribution of the water table was considered null when its average depth is ≥300 cm. The CLI indicator was finally calculated as follows:

$$CLI_{0-1} = \log AWC_{0-1} + WT_{0-1}. \quad (6)$$

2.2.4. Carbon sequestration potential

The carbon sequestration potential (CSP) was assessed following the approach proposed by Stolbovoy et al. (2005, 2006) modified as in Ungaro et al. (2010), considering a reference depth of 30 cm. The assessment is based on a set of simplified assumptions: (i) the pedolandscape units are different in soil organic carbon (SOC) content; (ii) SOC content results from the combination of pedolandscapes and land use (LU) and management; (iii) each combination has its specific SOC range; (iv) the SOC change in each combination is limited by a SOC specific range boundaries; (v) other conditions being equal, potential for the change depends on the actual SOC stock; (vi) reclaimed peat soils, typical of A2 landscape unit, were considered incapable to potentially sequester more carbon (Freibauer et al., 2004) and were excluded from calculations, and set to 0. In the approach presented here, we used the administrative boundaries of the 8 provinces of Emilia Romagna as a good proxy for dominant land use and management (Ungaro et al., 2010; Scalenghe et al., 2011) then considering the combination of l_i pedolandscapes and pi province levels (N = 80). Using these figures, it was possible to estimate the CSP for the reference depth of 30 cm. This was calculated for each cell of the grid as the difference between the 90th percentile of the reference combined spatial levels ($p_{0.9}SOCp_il_i$) any grid cell belongs to, and the SOC estimated for the same cell $SOC_{30}p_il_i$(x,y), where x and y are coordinates of the cell centroid. The CSP values (Mg C ha^{-1}) were then further standardised to the range [0,1] using the observed statistics at province level (i.e. maximum and minimum CSP) as reference level. Then, for each combination of pedolandscape l_i and province p_i the calculations were as follows:

$$CSP_{30} = p_{0.9}SOC_{30}p_il_i - SOC_{30}p_il_i(x,y) \quad (7)$$

$$CSP_{0-1} = [p_{0.9}SOC30p_il_i - SOC30p_il_i(x,y)] - \min CSP_{30}p_i / \min CSP_{30}p_i - \max CSP_{30}p_i. \quad (8)$$

2.2.5. Food provision

The assessment of potential food provision (PRO) is based on Land Capability Classification (LCC) classes, originally developed by the Soil Conservation Service of the U.S. Department of Agriculture (Klingelbiel and Montgomery, 1961), and adapted to local soil conditions (Guermandi, 2000). The LCC map is available at the scale 1:50,000 (Regione Emilia Romagna, 2010) for the plain areas. Approximately 56% of the area of the plain lies in classes with few (or none) limitations (I, II, I/II, II/I) for agricultural production. Areas with soils falling into classes not considered suitable for agricultural use accounts for less than 2% of the total area and are mainly attributable to Class V. In other cases the choice of possible crops is somehow limited to different extent. LCC classes were standardized following the scheme presented in Table 4.

2.2.6. Support for human infrastructures

Soil physical properties determine its capacity for supporting buildings, roads and other parts of human infrastructures over a given landscape (SUP). Among these, soil texture, permeability, the amount and quality of the clay fraction, and the presence of peat play a major role in the assessment of soil suitability for building purposes. In our case, as indicator of the capacity of soils in supporting shallow foundations buildings, roads and other infrastructures, we based upon the terrain classification scheme adopted in Italy as the reference for roads construction based upon the American Association of State Highway and Transportation Officials System (CNR UNI, 10006, 2002). It groups soils on the basis of their similarity in load carrying capacity, taking into account granulometry, liquid limit, plasticity index, shrink-swell characteristics, permeability and the presence of peat.

Table 4
Land capability class (Regione Emilia Romagna, 2010) and associated scores for the indicator of food provision potential (PRO).

Land capability class	Index [0–1]	Area share
I	1	9.48%
I/II	0.95	5.94%
II	0.80	39.76%
II/I	0.90	5.16%
II/III	0.70	8.21%
II/III/IV	0.65	0.04%
II/IV	0.55	0.37%
III	0.60	19.60%
III/II	0.65	3.38%
III/II/IV	0.57	0.03%
III/IV	0.50	3.69%
III/VI	0.30	0.03%
IV	0.40	0.88%
IV/II	0.52	0.15%
IV/III	0.50	0.96%
IV/VI	0.27	0.02%
V	0.30	2.12%
V/II	0.35	0.05%
VI/IV	0.25	0.05%
VIII	0.00	0.07%

The normalised indicator, for a reference depth of 100 cm, was calculated taking into account the hydraulic saturated conductivity (K_{sat}), coarse fragments, sand content and clay content, as proxy for shrink-swell character. Based on regional soil data, a threshold was set on soil organic carbon (SOC) stock at 300 Mg ha^{-1} for excluding peat. In order to deal with the highly asymmetric distribution of estimated K_{sat} (skewness = 5.46), the values, calculated resorting a PTF from literature (Rawls and Brakensiek, 1989), were log-transformed prior to interval normalisation. The calculation of the service indicator was then as follows:

$$\mathrm{SUP}_{0\text{–}1} = (\mathrm{Log\,Ksat}_{0\text{–}1} + \mathrm{Coarse\,fragments}_{0\text{–}1} + \mathrm{Sand}_{0\text{–}1} - \mathrm{Clay}_{0\text{–}1}) \quad (9)$$

for SOC stock <300 Mg ha^{-1}, and as:

$$\mathrm{SUP}_{0\text{–}1} = 0 \quad (10)$$

for SOC stock ≥300 Mg ha^{-1}.

2.2.7. Water storage and water regulation

Among the regulating soil functions, those affecting the water cycle contribute in providing fundamental ecosystem services, such as the control of floods and droughts (Daily et al., 1997; CEC, 2006). As indicator of the potential of soil in storing water, water storage (WAS), the volumetric soil water content at field capacity (−33 kPa tension), WC_{FC} ($m^3\ m^{-3}$), was considered. WC_{FC} was calculated using a locally calibrated point PTF (Ungaro et al., 2005), whose inputs are soil texture, organic carbon content and bulk density, for a reference depth of 100 cm. The estimated value was then linearly decreased by the coarse fragments volumetric fraction (*sk*, vol vol^{-1}). In case of presence of the shallow water table in the first 1 m of soil, its average depth WT (cm) was taken into account for further decreasing the overall soil potential of storing water.

WAS $_{0\text{–}1}$ was eventually calculated, as follows:

$$\mathrm{WAS}_{0\text{–}1} = (\mathrm{WC}_{FC} * (1 - sk))_{0\text{–}1} \quad (11)$$

for water table deeper than 100 cm, and

$$\mathrm{WAS}_{0\text{–}1} = (\mathrm{WC}_{FC} * (1 - sk) * (WT/100)) \quad (12)$$

for water table within the first 100 cm.

Soil regulates the fraction of precipitation water which infiltrates, thus regulating runoff, transport of nutrients, pollutants and sediments, and contributing to groundwater recharge. Soil infiltration depends on various factors, such, e.g., moisture conditions, soil structure characteristics (included artificially created tillage clods) and stability, beside soil cover and precipitation characteristics, duration and intensity (Hillel, 1998). The infiltration process depends mainly on three parameters: saturated hydraulic conductivity, net capillary drive, and soil saturation conditions. At the beginning of a storm and before ponding conditions, the infiltration rate is equal to the precipitation rate. When the ponding conditions are reached, soil reaches the maximum infiltration capacity, which equals the saturated hydraulic conductivity when the whole soil profile is saturated. The maximum rate at which water can enter the soil, or infiltration capacity, f_c (mm h^{-1}) is described by Smith and Parlange (1978), as reported in Morgan et al. (1998):

$$f_c = K_{sat} * (\exp(F/B)/(exp * (F/B) - 1) \quad (13)$$

where K_{sat} (mm h^{-1}) is the saturated hydraulic conductivity, *F* is the amount of rain already infiltrated in the soil (mm) and *B* is given by:

$$\mathrm{B} = G * (\mathrm{Theta}_s - \mathrm{Theta}_i) \quad (14)$$

where Theta_s ($m^3\ m^{-3}$) is the soil water content at saturation and Theta_i ($m^3\ m^{-3}$) is the initial water content. The term *G* (mm) is the net capillary drive or wetting front suction, calculated as (Hantush and Kalin, 2005):

$$G = \mathrm{PSI_e}[(2 + 3\lambda)/(1 + 3\lambda)] \quad (15)$$

where $\mathrm{PSI_e}$ is the air entry potential (mm, kept positive), and λ (−) is the pore size distribution index. The parameter *G* is therefore correlated to $\mathrm{PSI_e}$; based on a local dataset of 444 measured soil water retention curves (Ungaro et al., 2005), the correlation (R^2 = 0.98) is:

$$G = 1.5795 * (\mathrm{PSI_e})^{1.0104}. \quad (16)$$

As indicator for the potential of soil in regulating the rainfall water (WAR) we eventually considered the estimated (Rawls and Brakensiek, 1989) soil hydraulic saturated conductivity (K_{sat}, mm h^{-1}) combined with the estimated (Ungaro et al., 2005) potential at air entry point (mm, $\mathrm{PSI_e}$). In order to deal with the highly asymmetric distribution of measured K_{sat} (skewness 5.46), the values of K_{sat} were log-transformed. The water regulation capability of the soils ($\mathrm{WAR}_{0\text{–}1}$) was then calculated as follows:

$$\mathrm{WAR}_{0\text{–}1} = \log K_{sat\,0\text{–}1} - \mathrm{PSI}_{e0\text{–}1}. \quad (17)$$

2.3. Urbanisation

Assuming that the soils sealed by urbanisation are not capable to provide any ecosystem service, as they lost their multi-functionality, we used the urban land use class (URB) of the Emilia Romagna Land use map (Fig. 2, Regione Emilia Romagna, 2011) to weigh the indicator values. In each 1 ∗ 1 km cell the relative fraction (range 0–1) occupied by built areas (Ungaro et al., 2014a) was considered and used to rescale each indicator as follows:

$$\mathrm{Indicator\_final} = \mathrm{Indicator} * \mathrm{URB}_{0\text{–}1}.$$

2.4. Soil functions hotspots

The term "hotspots" proposed in the field of biodiversity (Egoh et al., 2008) and widely used to prioritise areas for biodiversity conservation is here used in the wider sense of "areas that provide large components of a particular service" (Bai et al., 2011). Different approaches can be used to delineate hotspots on maps (Baral et al., 2013; Egoh et al., 2008; Gimona and van der Horst, 2007; Ungaro et al., 2014b; Wu et al., 2013). In our case, ranging the indicators along a scale from 0 to 1, we considered the upper deciles of the observed indicators distribution, as physical thresholds wouldn't be meaningful. Hotspots were then identified and mapped for each single indicator as areas where their normalised values are above the 90th, 80th and 70th percentile of observed distribution (Anderson et al., 2009), i.e. the grid cell values that are on the top 10%, 20% and 30% respectively of all cells.

3. Results and discussion

3.1. Mapping the potential contribution of soil to ecosystem services supply

In Fig. 3a–h, maps for the selected function indicators are depicted. Clear patterns in functions provision are identified, linked to different pedolandscape units: different soils provide different functions to significantly different extents.

Table 5 reports the descriptive statistics for the eight selected function indicators estimated for the whole area and for the different pedolandscape units of the plain; the pie charts in Fig. 4a–h show the average supply for each unit as weighted over its actual area shares in the whole plain. In the figures, the lengths of the single slices in the

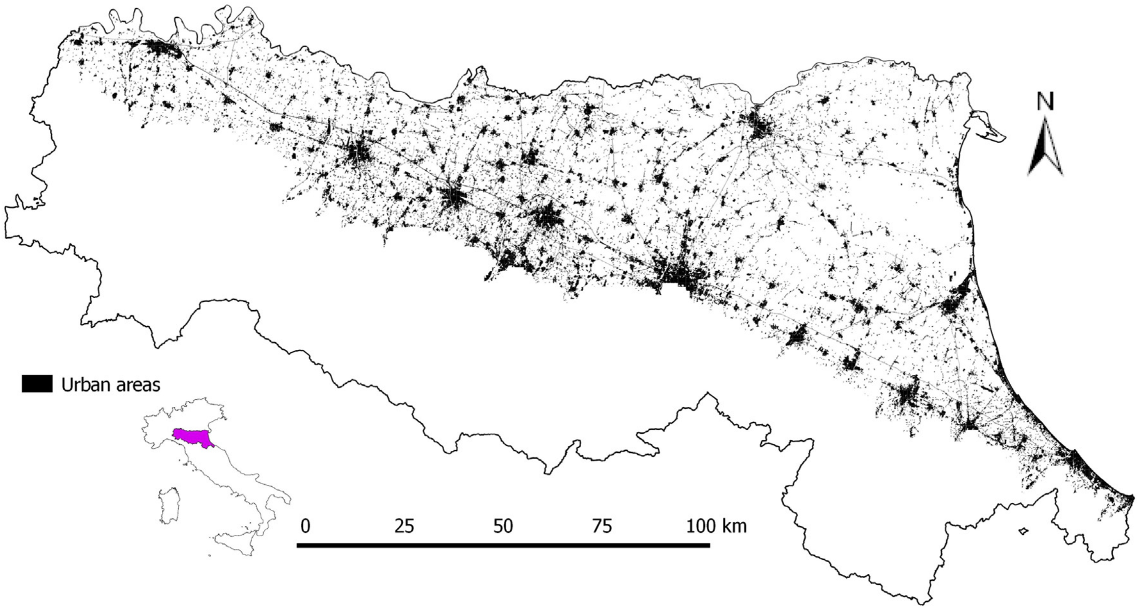

Fig. 2. Emilia-Romagna plain: urban areas.
Regione Emilia Romagna, 2011, mod.

pie chart are proportional to the mean value of the indicator, while their width is proportional to their area.

The figures show that the indicators chosen for each function are able to discriminate among the various pedolandscapes. In particular, the potential habitat for soil organisms (BIO, global average 0.41), which is by definition linked to land use, is significantly higher in traditionally more extensively cultivated areas, such as those under grasslands (permanent or, more frequently, in rotation) in the north eastern part of the plain or by no tilled orchards in the south western areas. The filtering and buffering potential of soils (BUF, global mean 0.44) is significantly higher ($p < 0.01$, Tukey–Kramer HSD test for unbalanced N) in areas of depressions of alluvial plains (units A4, A5a and A5b, mean 0.63, 0.62 and 0.61 respectively) and in soils rich in organic matter of the recently reclaimed areas (A2, mean 0.60). Conversely BUF is lower in coastal areas soils (unit A1, 0.18) and on the units of the Apennines' alluvial fans (A9a and A10, mean 0.30 and 0.31 respectively). The soils' potential contribution to microclimate regulation (CLI, global mean 0.38), being linked to the average depth of shallow water table, is higher in areas where water table is on average closer to the surface, i.e. in the distal part of the Emilia-Romagna plain. However, significant differences exist among all the landscape units, linked to the inherent properties of the soils. The carbon sequestration potential, CSP, is on average low in the whole plain (mean 0.24) except on the generally coarse textured soils of coastal plain, unit A1 (mean 0.38), and in the generally loamy textured soils of meander plain of Po river, unit A3 (mean 0.28). The high values of the CSP indicator for the soils of the unit 4Ac is due to the high heterogeneity of OC content of this unit, which encompass soils with contrasting OC contents, which increases in the eastern part of the unit along the margins of recently reclaimed organic soils. As high spatial variability cannot be properly resolved at this scale of investigation, and stemming the indicator CSP from a difference of order statistics, this results in high values which can be not fully realistic at local scale.

The potential food provision (PRO) of the soils of alluvial plains of Emilia-Romagna is on average high (mean 0.62), but significant differences exist between soils on levees (units A4c, A5a and A5b (mean 0.67, 0.77 and 0.65 respectively)), which show significantly higher values ($p < 0.01$) as compared to soils of depressions (units A4, A6a and A6b, mean 0.59 in the three units) and of terraced areas (unit A9a, mean 0.59) and alluvial fans (unit A8c, mean 0.55) and to soils of coastal (unit A1, mean 0.50) and of reclaimed areas (unit A2, mean 0.49).

As regards the potential support to human infrastructures (SUP), this is significantly higher ($p < 0.01$) in relatively coarser textured soils along the Po river (unit A3, mean 0.50) along the coast (unit A1, mean 0.59), and in general the recent levees' unit A5a (mean 0.42). Also the highly differentiated profile soils of alluvial gravelly terraced fans (unit A9a, mean 0.53) show SUP values above the global value of the plain (mean 0.36). Given the assumptions in the computation of the indicator, all the fine textured units and the units characterised by the presence of peats are scored with values below the global average.

Water regulation potential (WAR, global average 0.46) shows the lower mean values in fine textured soils of the depressions (units A4, A6a and A6b, mean 0.32, 0.34 and 0.37 respectively) and the higher mean values in coarse textured soils of coastal plains (unit A1, mean 0.64) and in the recent reclaimed areas of unit A2 (mean 0.79).

Finally, water storage potential (WAS, global average 0.43) shows on average a complementary behaviour to that observed for WAR, with significantly ($p < 0.01$) higher values in finer textured soil of the depressions of both Po (unit A4, mean 0.55) and Apennine (A6a and A6b, means 0.53 and 0.52 respectively) alluvial plains. The highest value for WAS is observed for the organic matter rich soils of unit A2 (mean 0.66). The lowest WAS values are associated to coarse textured soils of coastal plains (unit A1, mean 0.19) while intermediate mean values characterise the soils of the levee areas of Po river (unit A4c, mean 0.46) and Apennines (A5a and A5b, means 0.42 and 0.44 respectively) alluvial plains, and of terraced areas and alluvial fans of Appennines with lower values in soils rich in coarse fragments (unit A9a, mean 0.30).

As for synergies and trade-offs (Bennet et al., 2009) at a global level, i.e. for the whole case study area, BIO is synergic with WAS and BUF while trade-offs are observed with CSP and SUP; these facts are due to simultaneous responses of different sign to the same drivers, i. e. clay content, organic carbon content and bulk density. The same apply to the strong synergies observed between WAS and BUF, WAS and CLI, and between BUF and CLI. Significant interactions ($p < 0.01$) among functions are observed between PRO, on one side, and WAS, WAR and BUF, on the other: in this cases the provision of the latter functions affect the level of provision of the former. Significant interactions, which are relevant for planning and management as supporting infrastructures

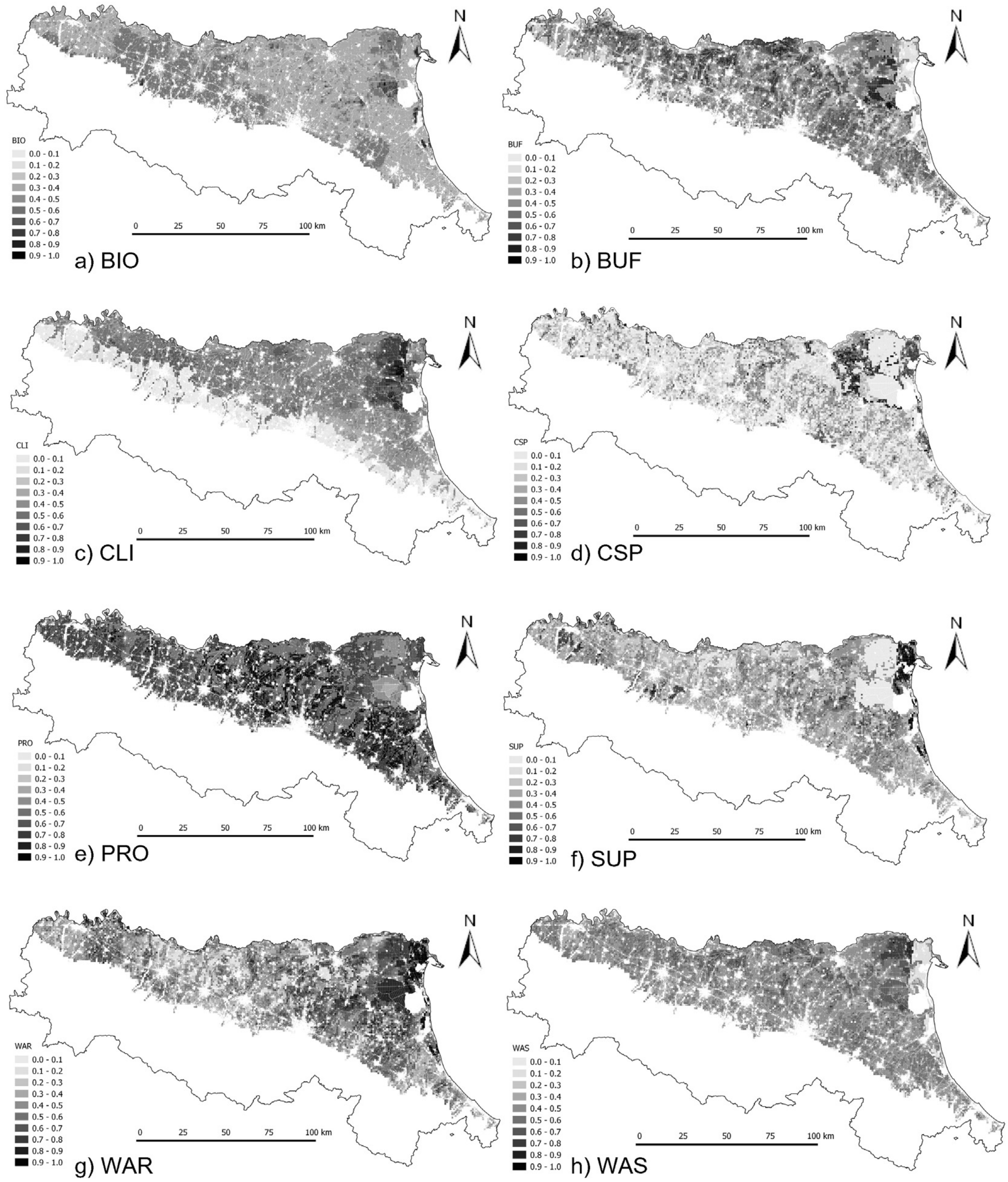

Fig. 3. Maps of soil functions. a) BIO: habitat for soil organisms; b) BUF: nutrient and pollutant retention and release; c) CLI: microclimate regulation; d) CSP: carbon sequestration potential; e) PRO: food provision; f) SUP: supporting human activities and infrastructures; g) WAR: runoff and flood control; h) WAS: water storage.

Table 5
Descriptive statistics of estimated potential supply of eight soil functions in the pedolandscapes of the Emilia-Romagna plain.

		BIO		BUF		CLI		CSP		PRO		SUP		WAR		WAS	
Pedolandscapes	N	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
A1	555	0.379	0.160	0.182	0.171	0.371	0.118	0.376	0.296	0.502	0.154	0.585	0.211	0.638	0.168	0.193	0.158
A2	473	0.542	0.088	0.598	0.193	0.754	0.091	0.000	0.000	0.485	0.051	0.027	0.123	0.790	0.078	0.659	0.100
A3	583	0.355	0.128	0.338	0.107	0.485	0.068	0.280	0.243	0.485	0.224	0.501	0.120	0.575	0.139	0.398	0.077
A4	357	0.408	0.048	0.632	0.111	0.497	0.059	0.211	0.161	0.585	0.039	0.270	0.124	0.324	0.185	0.552	0.063
A4c	856	0.378	0.044	0.440	0.123	0.539	0.085	0.499	0.336	0.672	0.079	0.319	0.258	0.560	0.140	0.455	0.072
A5a	2992	0.390	0.062	0.419	0.090	0.446	0.068	0.224	0.182	0.765	0.133	0.422	0.104	0.509	0.155	0.420	0.050
A5b	847	0.425	0.076	0.473	0.102	0.455	0.075	0.210	0.176	0.646	0.122	0.341	0.100	0.394	0.169	0.442	0.045
A6a	1249	0.425	0.067	0.623	0.084	0.473	0.071	0.233	0.176	0.587	0.079	0.280	0.110	0.337	0.180	0.534	0.062
A6b	254	0.446	0.075	0.612	0.099	0.482	0.056	0.224	0.169	0.586	0.076	0.280	0.100	0.367	0.155	0.517	0.054
A7a	718	0.374	0.106	0.345	0.070	0.383	0.100	0.169	0.172	0.482	0.100	0.358	0.110	0.408	0.129	0.345	0.065
A8	915	0.417	0.087	0.423	0.070	0.079	0.021	0.204	0.179	0.588	0.082	0.318	0.087	0.373	0.136	0.390	0.054
A8c	714	0.400	0.093	0.411	0.105	0.070	0.029	0.208	0.212	0.545	0.105	0.289	0.109	0.338	0.147	0.377	0.069
A9a	291	0.404	0.080	0.300	0.107	0.044	0.036	0.189	0.218	0.585	0.060	0.527	0.162	0.358	0.117	0.299	0.072
A10	641	0.456	0.085	0.306	0.164	0.084	0.024	0.219	0.189	0.555	0.123	0.337	0.068	0.381	0.114	0.411	0.113
All	11,445	0.406	0.093	0.436	0.148	0.383	0.204	0.238	0.233	0.616	0.157	0.358	0.193	0.459	0.196	0.427	0.102

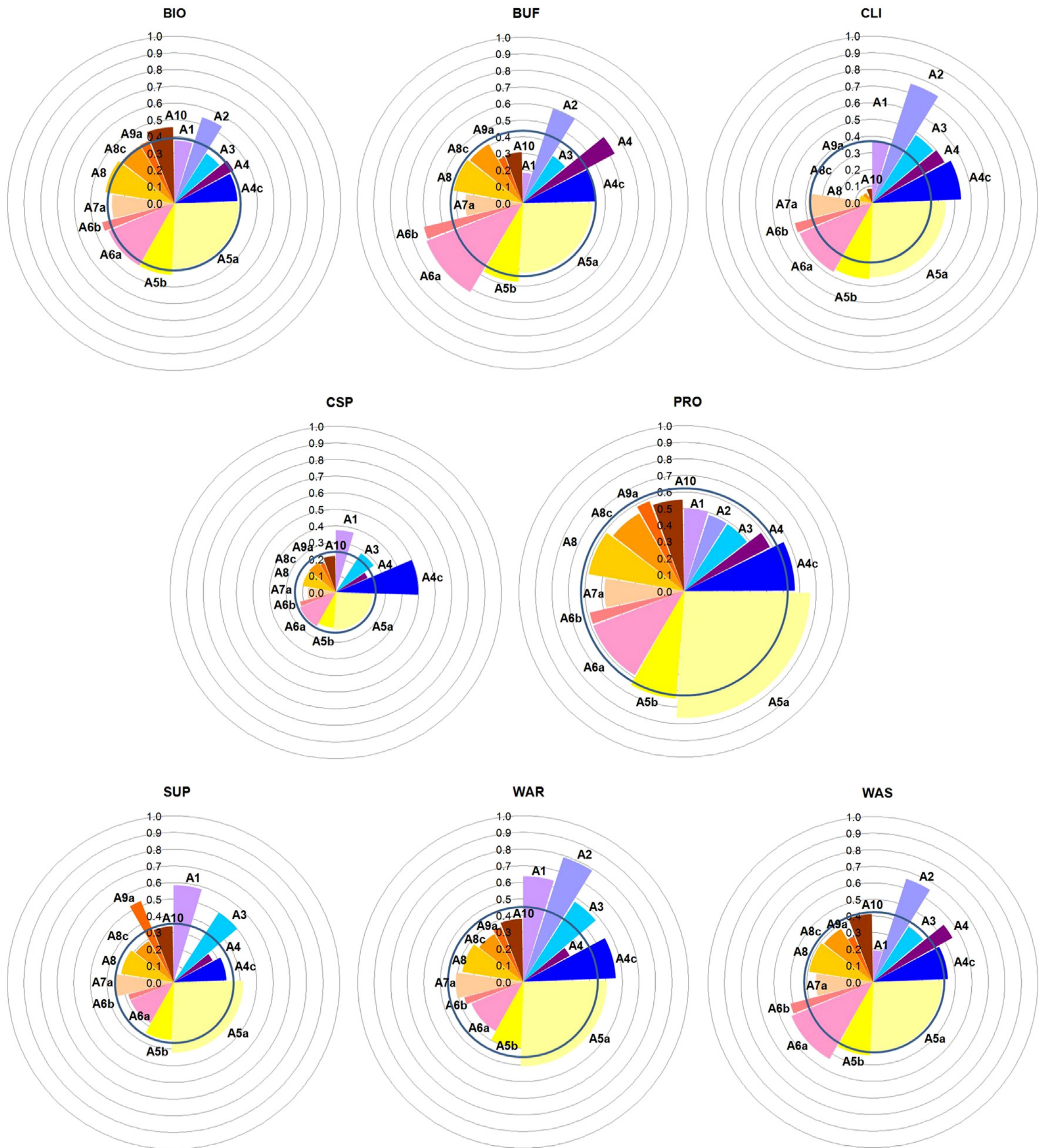

Fig. 4. Average supply of soil functions in the pedolandscape units of the Emilia-Romagna plain (continuous circles represent the global average of the whole area). a) BIO: habitat for soil organisms; b) BUF: nutrient and pollutant retention and release; c) CLI: microclimate regulation; d) CSP: carbon sequestration potential; e) PRO: food provision; f) SUP: supporting human activities and infrastructures; g) WAR: runoff and flood control; h) WAS: water storage.

often results in complete loss of other soil functions, are those observed for SUP and WAR and PRO. In Fig. 5, the web charts summarise the joint soil functions average supply in some relevant pedolandscape units of the Emilia Romagna plain, highlighting the existence of different potential contribution to the supply of services among units and of specific trade-offs, synergies and interactions among services.

Unit A1 (coarse textured soils of the coastal plain) is characterised by a marked polarization in the provision of two functions, synergic but actually mutually exclusive, namely WAR and SUP, followed by CSP; all the others considered in this study are below the global average, with the exception of CLI which is almost coincident with the global average. Unit A2 (fine textured soils with organic layers and peat) exhibits an above average potential provision of CLI, BUF and BIO, while SUP and CSP are significantly below the global average. In this unit significant trade-offs are observed among many couples of functions, e.g. SUP and WAR, SUP and WAS, SUP and BUF, SUP and CLI, while negative interactions are observed for PRO and WAR, BIO and BUF, CSP and SUP, BIO and SUP. Synergies are observed between WAR and CSP, WAR and BIO, CLI and WAS, and CLI and CSP. The units A5a (loamy textured soils of the levee areas of the plain) and A6a (fine textured soils of the depressions of the plain), being the most widespread units, are those closer to the global average in terms of potential contribution to service supply with some differences nevertheless. In unit A5a PRO and WAR rank highest among the functions, while in unit A6a this is observed for BUF and CLI. Furthermore in this unit, clear trade-offs, not observed in unit A5a nor at global level, are detected between WAR and WAS, WAR and BUF, SUP and WAS and SUP and BUF. Both units A8 (loamy textured soils with skeleton of alluvial fans of the Apennines) and A10 (moderately fine to fine textured strongly weathered soils of the Apennines margin) are characterised by potential contribution to service supply below the global average for nearly all the considered functions, with the exception of BIO which is slightly

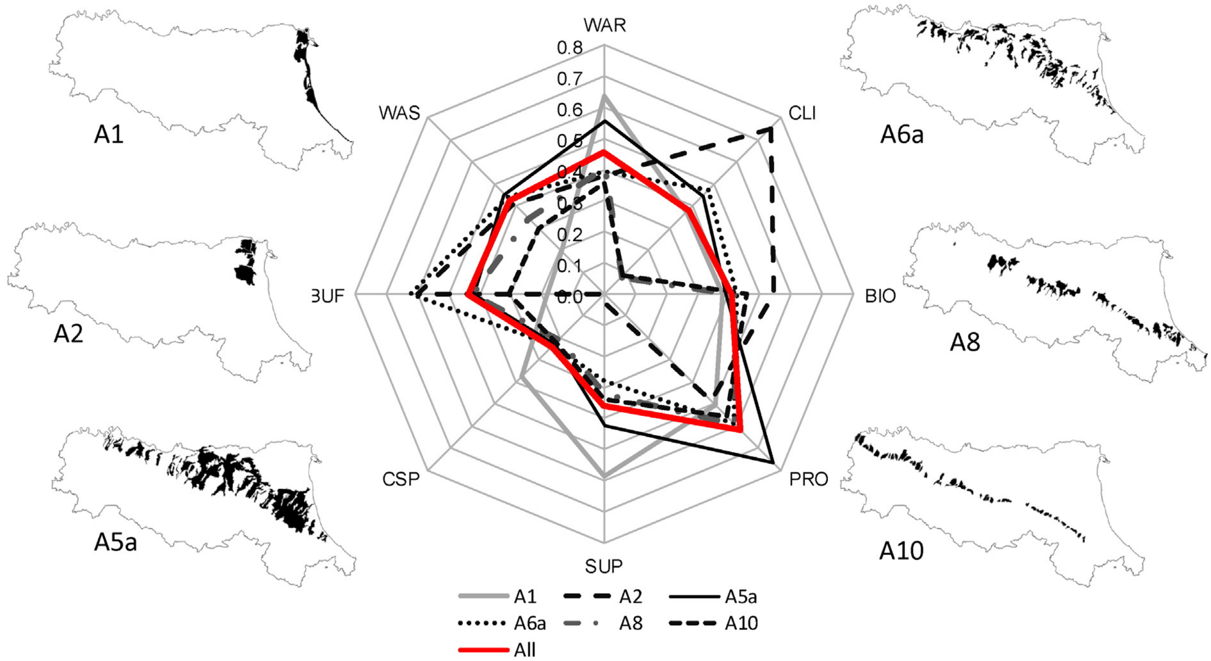

Fig. 5. Joint soil functions average supply in six relevant and contrasting pedolandscape units of the Emilia-Romagna plain: synergies and trade-offs (A1: coarse textured soils of coastal plain; A2: Fine textured soils of the recently reclaimed areas of the Po river delta plain, with organic layers and peat; A5a: Loamy textured soils of the levee areas of the Apennines recent alluvial plain; A6a: fine textured soils of the former depressions of the Apennines recent alluvial plain; A8: Loamy textured soils of alluvial fans of Apennines, with rock fragments at variable depth; A10: Moderately fine to fine textured soils of the Apennine margin, with strongly differentiated profile).

above the figures observed for the whole area. In the case of PRO, SUP and CSP provision though, differences with the global average are not significant, while significantly lower supply is observed for CLI, WAS and WAR in both units, and for BUF in A10.

3.2. Hotspots of potential contribution of soils to ecosystem services supply

Table 6 reports the occurrence of hotspots of functions provision, i.e. the number of grid cells which present different numbers of joint functions provided for different thresholds based upon order statistics, i.e. the 9th, the 8th, the 7th and the 5th decile of the observed distribution of each indicator for the whole area. The results in Table 6 show that in the case study area, in about 88% of the grid cells soil provides at least one function at a threshold value equal to the median of the distribution of each indicator. For the same threshold, 65.7% of the cells provide at least 4 services and 1.5% of cells provide all the eight considered functions. Considering as threshold the upper 10% of the observed distributions, 3.75% of the cells provide at least 4 functions, while considering as threshold the upper 30% of the observed distribution, 29.3% of cells provide at least 4 functions.

Table 6
Function bundles areas and % of total area under different thresholds for hotspots identification.

Number of functions	Top 10% overlap		Top 20% overlap		Top 30% overlap		Median overlap	
	km^2	% total	km^2	% total	km^2	% total	km^2	% total
0	6788	56.84%	3983	33.35%	2491	20.86%	1529	12.80%
1	2716	22.74%	2454	20.55%	1618	13.55%	829	6.94%
2	1240	10.38%	2339	19.58%	2116	17.72%	623	5.22%
3	751	6.29%	1650	13.82%	2217	18.56%	1116	9.34%
4	423	3.54%	1149	9.62%	2296	19.22%	2201	18.43%
5	25	0.21%	362	3.03%	1134	9.50%	2957	24.76%
6	0	0.00%	6	0.05%	70	0.59%	1696	14.20%
7	0	0.00%	0	0.00%	1	0.01%	818	6.85%
8	0	0.00%	0	0.00%	0	0.00%	174	1.46%
Multiple (≥4)	448	3.75%	1517	12.70%	3501	29.31%	7846	65.70%

The choice on the best threshold for identifying hotspots should be consistent with the aims of the classification. In Fig. 6a–d, the hotspots maps of Emilia-Romagna plain are reported, using the threshold of 10, 20, 30 and 50%, together with the web charts showing the average number of functions provided by each pedolandscape unit.

In all cases the average number of joint functions decreases as the threshold for hotspot identification increases, with a rate of decrease which differs in the different units. From the figures (Table 7), it results that a number of units, regardless of the threshold chosen for hotspots identification, rank high in terms of supply of joint functions (i.e. units A2, A4c, A6b and A4), while some units, regardless of the threshold, represents cold spots of joint functions supply (i.e. A10, A8c, A8 and A7a). Nevertheless in few units, namely A1, A9a and A5b, the occurrence of hotspots for joint functions supply is strongly dependent upon the selection of the threshold for hotspots identification.

This results from the differences in the spatial interactions among indicators in terms of synergies and trade-offs in each pedolandscape unit, which determine the contribution of each indicator to the supply of multiple functions under different thresholds at specific locations. The overlapping of clusters of high (or low) values for a number of indicators results then in the supply (or lack) of joint functions at specific locations within each mapping units. The occurrence and the incidence of extreme values depends on the shape of the observed distributions of each indicator in each pedo-landscape unit. The co-occurrence within the same unit of rather uniform, positively or weekly skewed, and flatter (platykurtic) distributions for a number of indicators with markedly negatively skewed and leptokurtic distributions for other indicators, results in a greater sensitivity to the choice of the threshold for hotspots identification.

4. Conclusions

The growing need to support decision makers with information about the flows of ecosystem services has lead in the last decade to the development of more integrated analytical frameworks of the trade-offs between the environmental, economic, social and cultural outcomes of land planning (Adams et al., 2014; De Groot, 2006;

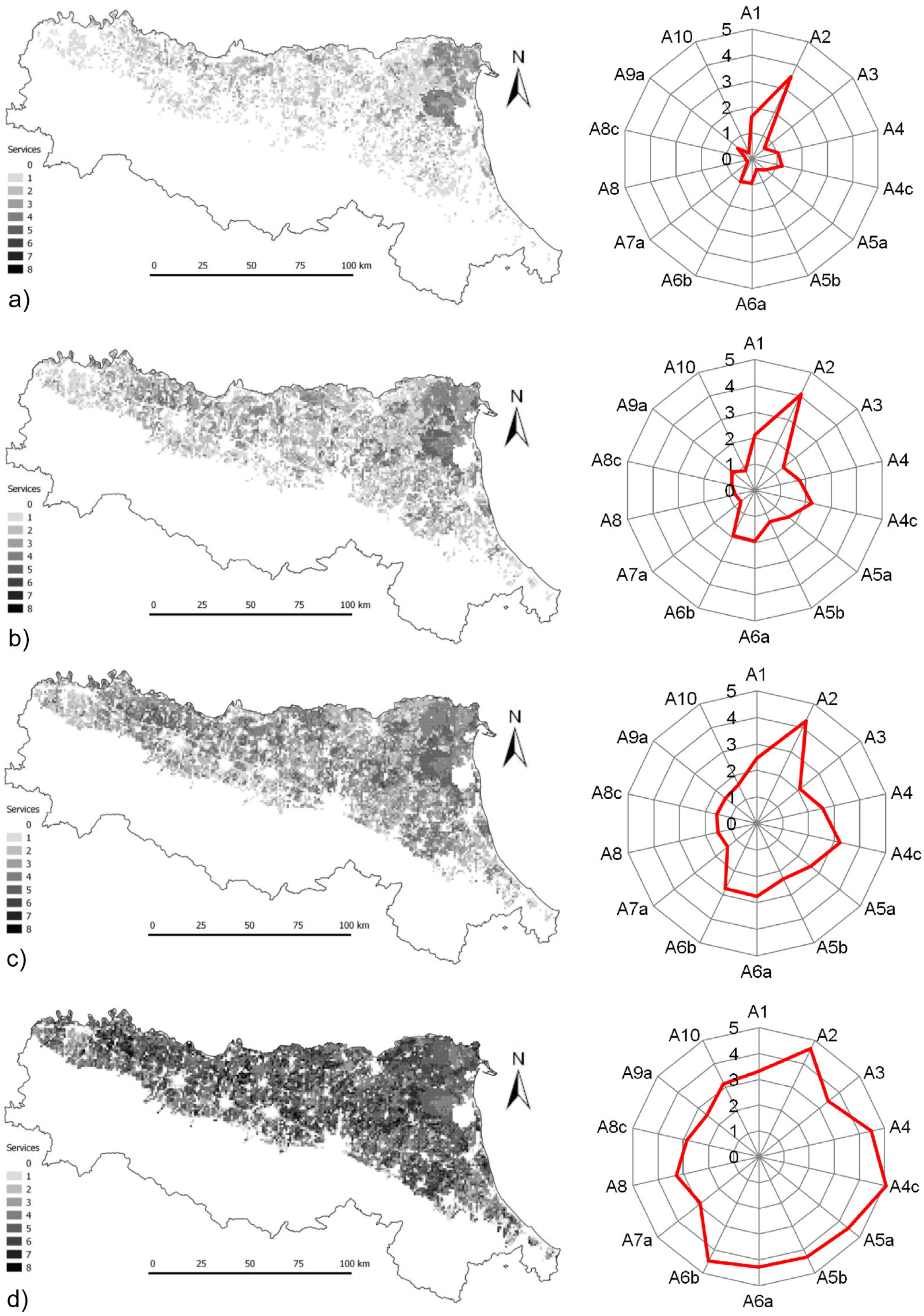

Fig. 6. Average number of functions provided by pedolandscapes: hotspots and function bundles under different order statistics thresholds (a) 10%; b) 20%; c) 30%; d) 50%).

Forouzangohar et al., 2014; Rahmanipour et al., 2014), and only recently the role of soil has been explicitly put at the core of such theoretical frameworks (Samarasinghe et al., 2013).

In this paper we present a set of soil functions indicators as the first step required for the assessment of ecosystem service supply once land use and management are considered.

The presented approach has the advantage of simultaneously consider the multiple contribution of soil to ecosystem services in a spatially explicit way, i.e. location specific, using indicators based on available data, soil and land use maps and a set of locally calibrated PTFs coupled with geostatistical estimates at unsampled locations. The approach represents in our view an advance as it represents a further step towards the operational implementation of existing soil based ecosystem services theoretical frameworks (Dominati, 2013) building on available data and existing knowledge. The presented approach can be viewed as a recalibration of classical land evaluation schemes (Rossiter, 1996) in which an ecosystem approach is tailored to take into account specific soil properties which underpin specific services through the use of specific indicators calibrated on local soil variability. In doing so we considered one of the spatial scale, the regional one, which is more relevant to the decision-making process in agreement with local stakeholders, and proceeded with a top-down approach to characterise the spatial

Table 7
Supply of joint functions and ranks under different thresholds.

Units	Functions under thresholds				Rank under thresholds				Average	Std. Dev.
	90%	80%	70%	50%	90%	80%	70%	50%		
A2	4	4	4	5	1	1	1	2	1.25	0.50
A1	2	2	2	3	2	3	7	9	5.25	3.30
A4c	1	2	3	5	3	2	2	1	2.00	0.82
A4	1	2	3	4	4	6	6	4	5.00	1.15
A6b	1	2	3	4	5	5	4	3	4.25	0.96
A6a	1	2	3	4	6	4	3	7	5.00	1.83
A5a	1	2	3	4	7	7	5	5	6.00	1.15
A9a	1	1	2	3	8	10	12	14	11.00	2.58
A3	1	1	2	3	9	8	9	8	8.50	0.58
A5b	0	1	2	4	10	9	8	6	8.25	1.71
A8c	0	1	2	3	11	11	11	13	11.50	1.00
A10	0	1	2	3	12	12	10	11	11.25	0.96
A8	0	1	2	3	13	13	13	10	12.25	1.50
A7a	0	1	1	3	14	14	14	12	13.50	1.00

heterogeneity of soil functions (Baveye and Laba, 2014). The approach allows to establish clear links between decisions and potential supply of ecosystem services as it makes clear where and to which extent different functions are provided by different soils, allowing to assess the risk of service loss or the chance of service maintenance or enhancement under different external drivers, such as policy and management options.

Although not considered in our approach, the flow of services stemming from soil stocks, could, under certain conditions and with some limitations, be quantified in monetary terms (Robinson et al., 2014), allowing the possibility to address the issue under a more strictly economic focus. However, while a valuation system based on a diversity of criteria has the advantage of taking into account the diversity of stakeholder perspective on the relationships between soils and society (Barnaud and Antona, 2014), a strictly monetary valuation can only grasp a limited aspect of the whole value of an ecosystem or service (de Groot et al., 2010).

A limitation of the proposed approach is that at the adopted working scale is not easy to validate the results. However, pedolandscape units show significant different behaviours as regards most of the selected indicators, and this in good agreement with the local soil knowledge. A further limitation of this method is the relative subjectivity, both in identifying the indicators and in their calculation. However, the indicators were chosen on the base of well established schemes and developed at a spatial scale suitable with available data on one side and with the identification of planning strategies on the other. The indicators were then thoroughly discussed with the regional soil service, and the results assessed on the base of local knowledge and decision context. The framework is flexible, in defining indicators and in calculating them. It can be used at different spatial scales and is capable to integrate new knowledge when available. For example the approach can be easily implemented at municipality level in order to assess the impact of soil sealing in terms of functions loss associated, for example, to new building infrastructures or to better target compensation measures to be taken in order to restore the flow of soil based ecosystem services and to support sustainable soil management.

Acknowledgements

The authors gratefully acknowledge Regione Emilia-Romagna, Servizio Geologico, Sismico e dei Suoli, for kindly providing basic soil data. Neither Regione Emilia-Romagna, nor any person acting on behalf of the Regione is responsible for the use which might be made of this publication.

The authors thank all the reviewers for their valuable and constructive contributions in improving the original manuscript.

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