Describing urban soils by a faceted system ensures more informed decision-making

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KEYWORDS: urban soils; soil information transfer; ecosystem services; soil functions; facets

ABSTRACT

Urban areas are increasing worldwide at a dramatic rate and their soils definitely deserve more attention than they have received in the past. In urban environments, soils potentially provide the same ecosystem services as in rural and wild environments, although in some cases they are depleted of their basic functions, such as when they lose their productive and filtering capacities because of sealing, and become mere supports for infrastructures. In other cases, soils of urban areas acquire new functions that are unique to these environments. Current soil classifications fail to effectively account for the complexity of urban soils and the information that is required for their management. Additionally, the survey of urban soils is difficult, due to fragmentation and rapid land use change and the fact that due to human pressure their properties seldom vary linearly and predictably according to landforms, which hinders the effectiveness of geostatistics. The conventional practice of grouping similar soils and transferring their information in a concise manner is not viable for urban soils. We advocate the introduction of a faceted system – i.e. a scheme using semantic categories, either general or subject-specific, that are combined to create the full classification entry – to organize the information on urban soils to support decision-making. The facets that such a system should be based on are not only the intrinsic physical and chemical properties that are usually used to describe any soil, but also other tangible or even immaterial properties that are particularly meaningful in an urban context, such as landscape metrics, or aesthetic, social and historical values. As well as providing more adequately the information of the type requested by urban planners and policymakers, a faceted system of classification of urban soil resources would have the flexibility to accommodate all available or future scattered, rapidly changing, or incomplete data.

1. Introduction

Soil provides food, biomass and raw materials to humankind. It is a platform for human activities, a main component of the landscape, an archive of heritage, a filter for groundwater quality, and the most important terrestrial storage of carbon and biodiversity. Soil stores, filters and transforms many substances, including water, nutrients and carbon (Commission of the European Communities, 2006). A thorough review of the literature about soil properties and the associated ecosystem services has been just compiled by Adhikari and Hartemink (2016). Soil sustains an expanding population that is increasingly living in cities (Anonymous, 2010; United Nations, 2014). As a consequence, urban areas are experiencing a progressive enlargement that involves peri-urban soils, completely removing or converting them to *urban* soils (Figure 1). In urban contexts, soils potentially provide the same ecosystem services as other soils but their role of physical support for infrastructures frequently overcomes all others (Grimm et al., 2008). In most cases, urban soils experience serious depletion of their basic functions, in particular biomass production, biodiversity conservation, and carbon sequestration. Therefore, urban soils are different, in many aspects, from their agricultural, forest or natural counterparts (e.g. Biasioli et al., 2006; Ellis, 2011; Pickett et al., 2011), so much so that the traditional approaches for describing and mapping them often seem inappropriate.

While in the countryside land use is mostly planned on the basis of the soil's intrinsic properties, in cities soil uses essentially depend on site location. However, cities are highly dynamic environments where soil use changes rather frequently due to the continuous reorganization of the urban tissue (Hollis, 1991; Norra and Stüben, 2003; Rossiter, 2007). Topsoil horizons are often reworked and obliterated, mixed with, or even replaced by, allochthonous materials (Nehls et al., 2013; Scharenbroch et al., 2005). Buildings and other infrastructures progressively sprawl in the country, sealing an increasing proportion of soils, making them unsuitable for performing crucial environmental purposes, such as draining rainwater or producing biomasses (Nuissl et al., 2009; Scalenghe and Ajmone-Marsan, 2009; Schmidt et al., 2004). As a consequence, urban soils appear fragmented and of very variable quality (European Environment Agency, 2011; Han, 2010; Kasanko et al., 2006; Kent, 2009). The patches of unsealed soils often experience some forms of degradation. For instance, a highway junction (Figure 1) degrades the soils of the area it includes by changing their hydrology and imposing severe contamination from traffic, but also dramatically affecting the access to animals and seeds. Overall, the functional, ecological and aesthetic meaning of the area is drastically modified. On the other hand, the issue of city sprawl (Anonymous, 2010) calls for a smarter, more compacted city design and encourages the reclamation and reuse of dismissed soils (Hou and Al-Tabbaa, 2014). Vast urban and peri-urban industrial areas are being dismissed in Western countries as a result of the evolution and delocalization of manufacturing activities. Such areas, usually called *brown-fields*, are sometimes reconverted to other uses after remediation action aimed at removing undesired or dangerous features.

Parks and gardens are another example of how urban soil functions are modified by urbanization. Green areas are highly appreciated in cities, where they improve air quality, mitigate urban heat and provide an agreeable environment for citizens (Qin et al., 2013; Tzoulas and James, 2010). They also play a role in enhancing the value of the neighbouring houses (Maruani and Amit-Cohen, 2013; Panduro and Veie, 2013). The *biomass production* function in urban settlements can then be as valuable as outside the city, but it acquires distinct features. The soils of parks and gardens, rather than producing an agricultural yield, are expected to provide welfare.

In reality, in urban settings the soils often fail to provide a suitable habitat for plants. Soil ecology and nutrient cycling in urban green areas are altered because of soil turbation, compaction, and pollution. Lorenz and Lal (2009) have reviewed data about the biogeochemical cycles of carbon and nitrogen in urban soils and revealed a great horizontal and vertical variability of both elements in view of the many human activities that can directly or indirectly alter those cycles. Carbon variability is usually much lower in the soils surrounding cities, in spite of the different requirements of crops (Scalenghe et al., 2011; Vasenev et al., 2014).

Contamination is another common feature of urban soils (Andersson et al., 2010; Costa et al., 2012; Giusti, 2011; Guillén et al., 2012; Qiao et al., 2011; Schwarz et al., 2012). The mapping of urban soil pollution was proposed as a medical tool for prevention purposes (Abrahams, 2006). Ajmone-Marsan and Biasioli (2010) collated a vast array of data about heavy metals' contamination in soils from 140 cities worldwide and found that most cities are contaminated by one or more trace elements. Organic pollutants are also common in the soils of urban and peri-urban areas (Morillo et al., 2007; Wang et al., 2013), confirming the environmental relevance of the urban soil system.

In summary, urban soils are required to provide more, and different, services than the classic ecological and productive functions for which the most widely used soil classification systems were born and have been developed. That is what makes it difficult to use these classifications with urban soils.

1.1. Soil classification in the urban context

Classification is a procedure to group material or immaterial things on the basis of shared characteristics. In hierarchical classifications, groups are distributed in ranks or categories, where the range of diagnostic properties of any group narrows as the system becomes more detailed. Soils are particularly difficult to categorize and map, since the variation of their properties in the landscape are more often continuous than discrete, which means that boundaries have to be arbitrarily established.

Soil classification was anecdotally born in 1877 in St Petersburg, Russia, when Vasily Vasili'evich Dokuchaev conducted the first pedological investigation (Arnold, 2006). The observation of zonal properties of climate, geology and vegetation was sufficient, at that time, to determine or infer general soil properties and the driving processes of soil formation on a large scale. Since that first rough form of classification, the *production function* of the soil was the pivot around which many of the ensuing classifications have been developed, given the importance of agriculture to humankind. One example is the Fertility Capability Soil Classification System (FCC), which classifies soils on the basis of attributes important for plant growth (Sanchez et al., 1982, 2003), or the Land Use Capability (LUC), which is mainly based on potential land uses (e.g. Curran-Cournane et al., 2014). There are other soil classifications. Some are of interest in engineering and geotechnics and are centred on the ability of soil to support buildings and roads or to deform because of earthquake-induced vibrations. Such classifications are based on soil texture (e.g. Chatterjee and Choudhury, 2013) or other properties related to the physical behaviour of soil (e.g. Boaga, 2013). Attempts have been made to classify soils according to their *filter*, *buffer* and *reactor* function, which allow transformations of components or solutes. In the case of landfill planning, soil productivity, biological activity, and soil permeability are normally the key parameters for sorting classes of suitability in this regard (Kara and Doratli, 2012; Moeinaddini et al., 2010). Vilček and Bujnovský (2014) have proposed a soil environmental index (SEI) to categorize soil's ability to retain water, immobilize pollutants and eventually transform them into less harmful forms. Such an index can be used for the assessment of ecological systems, planning of land use, and for expressing the economic benefits of individual ecosystems. The *resource function*, the capability to supply raw materials, is typically fatal to soil as it involves its total removal, and this would be the case for a drastic yes/no classification. The *habitat function*, i.e. the ability of soils to provide a living environment for plants and animals, is mirrored in the concept of soil biodiversity. The available information, however, is fragmented and a systematic organization of soils on a biological basis has not been hitherto attempted (Gardi et al., 2013; Jeffery, et al., 2010).

Modern soil classifications (IUSS Working Group WRB, 2014; Soil Survey Staff, 2014) are of the domain-analytic type and therefore are knowledge intensive (Hjørland, 2013a). They are based on the identification of a *diagnostic horizon*, i.e. a layer whose properties unequivocally reveal the combination of the chemical, physical and biological processes that transformed the original materials into a soil (viz. the *pedogenesis*).

Soils are usually named and classified directly in the field, based on the description of the sequence of genetic horizons and their pivotal properties (Table 1), as well as the identification of one or more diagnostic horizons. Soil properties are assumed to be homogeneous for a given area and their spatial homogeneity is usually inferred from site features, such as landforms, lithology, drainage, vegetation, land use, or surface soil features, such as colour or stoniness (Holmgren, 1988). On that basis, large-scale and progressively more detailed soil maps have been produced (Hartemink et al., 2013). A quantum leap in soil classification and mapping occurred with the use of computers and numerical classifications (Deng, 2007; Fitzpatrick, 1967). The general principles and scopes, however, remained focussed on agriculture. Soil science subsequently introduced geostatistics to define the boundaries of soil properties, based on an adequate number of samples and measurements. Soil mapping is better achieved by regionalizing the variables, rather than interpolating between points in space, using a stochastic model that considers the diverse spatial trends of the soil property of interest, e.g. the concentration of a single plant nutrient or pollutant. Such a method, known as *kriging*, is based on the assumption that near things are more interconnected than the distant ones (Cattle et al., 2002; Heuvelink and Webster, 2001).

Whatever the scope or the method, the current soil classifications are not able to account for the variety of soils occurring in urban settings (Figure 2). Perhaps more importantly, such classifications do not take into account many features and properties crucial for describing the potential and limitations of soils in the urban context, where diversity is so high that one could even conclude that soils *sensu stricto* are missing (Dudal et al., 2005). In extra-urban environments, several conceptual frameworks for the quantification of soil functions/ecosystem services have been successfully proposed (e.g. Kabisch, 2015; Schulte et al., 2014), but they are not applicable to cities, where random sampling of soils and representation of their unpredictable distribution are difficult goals. The requirement of identifying a diagnostic horizon to name soils at the highest hierarchical levels is a serious hindrance to classifying urban soils, as the original horizons are often being cancelled by human disturbances, or soil sampling is prevented by the superimposed artefacts. If a statistically representative sampling of soils is prevented, assuming spatial homogeneity is incorrect. Often, the recognition of urban soils as discrete entities (Aparin and Sukhacheva, 2014; Lebedeva and Gerasimova 2011; Lehmann and Stahr 2007) is implausible, as seldom do soil properties in urban settings show a linear, or any other type of regular variability, which is the *sine qua non* of geostatistics. In fact, soil surveys and mapping tend to exclude urban areas (Brevik et al., 2015), except for some local issues such as parks or other unpaved areas. Conventional soil maps represent urban areas as indistinct grey or black polygons that do not capture the internal soil complexity (Sanchez et al., 2009). On the scale of the European Soil Database 2.0, urban and peri-urban soils appear unsorted as endemic soil minorities (Ibáñez et al., 2013). Even in the more advanced means of cartographic representation, such as the smartphone app *mySoil* (Natural Environment Research Council, 2013), organized information about urban areas is often missing.

The crucial point is whether the diagnostic horizons and any soil features that are usually utilized to classify agricultural, forest or unmanaged soils are sufficient and all-meaningful for appropriately describing urban soils. As postulated by Bouma and Droogers (2007) a *regionalization of the approach to soil issues*, i.e. the development of methods that address local problems – and more specifically urban soil features – would facilitate contact with stakeholders and policymakers. A faceted system framework, i.e. a scheme using semantic categories, either general or subject-specific, that are combined to create the full classification entry, seems highly functional for categorizing urban soils and this paper discusses its viability (Figure 3). Contrary to classical enumerative classifications, which contain a full set of entries for all concepts, faceted classification (FC) systems use a set of semantically cohesive categories that are combined as needed to create an expression of a concept. In this way, a faceted classification is open, and not limited to already defined concepts.

2. A faceted classification for urban soils

The multiform and rapidly changing urban environments demand a new type of flexible soil categorization, functional for various and dynamic purposes (Arnold, 2006). Farmers are usually interested in soil fertility, hence in soil properties such as nutrients' supply, water retention, pH, organic matter content or particle size distribution, and these are generally provided by ordinary classifications, which also account for the soil formation processes. Urban soil users and stakeholders require additional or alternative information, which, in most cases, is peculiar to urban settings and is not taken into consideration by current soil taxonomies. A piece of land in the urban context can be evaluated from different points of views by different stakeholders, often representing contrasting interests. Nevertheless, none of them may be interested in the information about that soil provided by the classic classifications. For example, a property developer will mainly take the extent and the beauty of the area of interest and its surroundings into account, while a land planner will focus more on the topography of the area and the geochemical properties of its soils. Residents and potential buyers, on the other hand, are mainly interested in the beauty of the place and the type of facilities it benefits from (number and type of green areas, proximity to other services, i.e. degree of fragmentation/dispersion, distance to the nearest railway station and so on). A local Environmental Protection Agency pays attention to the type and degree of contamination to implement reclamation measures, while a municipality responsible for distributing allotments for private horticulture takes into account the size and shape of the area, soil fertility and contamination and, of course, the property rights. With time, financial, economic, demographic, and social changes may modify the interests of the various stakeholders towards a given urban soil more swiftly than any classical classification system (e.g. Brevik et al., 2015) can attest. The urban ecosystem depresses the importance of a few basic functions of soil, but often it broadens widens the variety of services that soil has to provide. The related information a classification must provide on urban soils must hence be even larger than that provided by normal soil classifications, in particular expanded to other characteristics. A faceted system seems to be the best tool for fulfilling this goal.

Faceted classification was proposed by Ranganathan (1967) to organize information about books and was used to classify various items, such as computer software, patents, books, and artworks (Kwasnik, 2002). Faceted classification is an advanced method of knowledge organization and information design and offers powerful and flexible information browsing and searching, and is particularly suitable for the Web (Slavic, 2008). A FC consists of reciprocally exclusive and jointly exhaustive categories, each one focused on a single aspect – a *facet* – of an item of an ensemble (Frické, 2013; Hjørland, 2013b; Perugini, 2010). Faceted classifications are widely used in e-commerce (Kwasnik, 2002; Vickery, 2008); for instance, amazon.com uses brand, price, seller, as individual facets but also has facets that are specific to the current result set (Table 2). In the case of soils, each one would be tagged with a set of attributes and values related to its natural, economic, technical, material or symbolic qualities, and its final characterization would hence depend on how the user accesses the faceted system. The soil *unit* for which the information is collected and retrieved can be identified on different bases. It can be a cadastral parcel or a Land Unit (the smallest unit of land that has a permanent, contiguous boundary, a common land cover and land management, a common owner), or any other subdivision or soil entity that is necessary or desirable to tag. A database of such objects and tags can be flexibly interrogated in various ways, according to the desired information retrieval. The advantages of a faceted classification applied to soils over other systems parallel those reported for bibliographic classifications (Broughton, 2006), i.e. i) the capacity to synthetically express the complexity of the object – and urban soils all in all are definitely very complex systems; ii) a syntax that allows for new facets to be easily introduced; iii) a logical structure that is compatible with both computer manipulation at whatever level (with geographical information systems in particular) and a graphical interface for end-user navigation and query formulation; iv) the facility to allow approaches from different angles (i.e. cross-domain query) and retrieve the set of all instances far more rapidly. However, Hjørland (2013a,b) has pointed out two main limitations of a FC system when applied to general knowledge organization, viz. i) the lack of an empirical basis and ii) a speculative ordering of knowledge which is not based in the development of theories. Its basic assumption that relations between concepts may be set a priori and not through models or theories appears to be questionable. ~~On the other hand, s~~Soil facets must be carefully chosen to make the system work properly. Discrete variables can only be used as facets or classes of continuous variables. Also, the facets need to be independent of each other so that any combination of values across facets is possible. This is not always true, e.g. for soil chemical properties, as some of the variables are correlated. In this case, just one of the correlated properties should be chosen as a facet. Within a facet, the values each facet may assume need to be dependent, i.e. they have to be mutually exclusive and, while this is true for chemical or biological properties, care must be taken that other properties are chosen to comply with this requirement.

Vickery (1960) proposed a faceted classification of soils based on 18 facets (in SI, Table 1S), mostly agriculture-oriented, but it was never fully developed. Here, we want to endorse the appropriateness of preparing and using a faceted system for the organization of knowledge about urban soils. Below we report a reasoned non-exhaustive list of facets that we feel are particularly meaningful for urban soils.

Physical and chemical properties

Soil thickness, stoniness, and particle size distribution appear to be crucial for urban soil description. Organic matter content, pH, and electrical conductivity (for salinity) are the most significant chemical soil traits. All of them are usually measured as continuous variables but can also be expressed as classes. For example, soil pH can be reported as acid, slightly acid, basic and so on, while the particle-size distribution can be reported as clay, silt-loamy, sandy, etc.

Pollution

The extent and degree of soil pollution and type of pollutants (heavy metals, hydrocarbons, radionuclides, etc.) are fundamental information for the use and management of urban soils. Basic threshold values can be the legislative concentration limits for contaminated soils. Further grades can, however, be adopted based on the results of an environmental risk assessment. A faceted system is particularly recommended for soil contamination in light of its adaptability to changes in legislation and the possibility to include values as they are obtained or other variables, i.e. previously ignored or unknown contaminants.

Landscape metrics

Landscape metrics are numeric measurements that quantify spatial patterning of land cover patches, land cover classes, or entire landscape mosaics of a geographic area (Lüscher et al., 2014; McGarigal and Marks, 1995). For example, the Class Area metric is a measure of landscape composition; specifically, how much of the landscape is comprised in a particular patch type (e.g. accessibility to main roads or proximity to nearby cities, as in Puertas et al., 2014).

The number of patches of a particular patch type is a simple measure of the extent of subdivision or fragmentation of that patch type, while the edge density is the edge length on a per-unit-area basis and facilitates comparison among landscapes of varying size (e.g. Borgogno-Mondino et al., 2015). Several other metrics can be used as facets of urban soils.

Ownership and other property rights

The faceted system for urban soils in terms of ownership may be based on a simple division into private and public, or include more information, such as right of way, partial usufruct, etc. Any information in this regard can be useful, for example, to a city administration that needs to tag soils with its ownership (temporary lease of rights, limits on the intended use, ownership conflict) or other planning characteristics.

Aesthetical value of the area

It is hard to think that the aesthetical value of an urban area does not have an influence on the judgement of its soils. Bartie et al. (2010) elaborated and proposed visibility modelling algorithms for urban environments, while Chamberlain and Meitner (2013) suggested a visibility analysis based on several simple landscape features, such as slope, aspect and distance from the observer, all of which could be facets for urban soils. An indirect method based on landscape pictures uploaded by users on the Internet has been proposed by Casalegno et al. (2013). Aesthetics will eventually influence the housing market, hence the relative soil facet might be based, at least partly, on the commercial value of the neighbouring houses.

Specific ecological functions

Modern urban planning envisages the creation of ecological (green) corridors, which represent precious shelters and connectors for wildlife (Groome, 1990). The soils of green corridors are, of course, expected to be safe and as fertile as possible, to sustain plant growth without the input of any chemicals and allow a healthy life for people and animals. To be part of a green corridor and to not be completely surrounded by sealed surfaces should be acknowledged as a highly positive feature of an urban soil.

Economic value

Urban land price is a result of natural, economic and social factors, and represents a source of information for planning (Hu et al., 2013). Monetary value is the most frequently quantified property of an urban soil, so facets can be derived from its multiple expressions, be they either real or estimated.

Social value

Given the mass of people gravitating to urban areas, here more than elsewhere soils may assume a high social value. Public green spaces play an important social role in the multifunctional and cultural services of urban ecosystems (Lundy and Wade, 2011), such as providing spiritual and psychological benefits as well as leisure and recreation opportunities. The most striking example of such an important role is perhaps that of community vegetable gardens, which are a unique intervention that can narrow the divide between people and the places where food is grown (Litt et al., 2011; Semenza and March, 2009). Indirect facets (e.g. human appropriation of net primary production, HANPP) can be used to account for the social value of urban soils (Niedertscheider and Erb, 2014), which is usually determined by hedonic pricing and contingent valuation (Brander and Koetse, 2011).

Historical value

The intrinsic value of an urban soil can be chiefly due to the presence of valuable ancient artefacts, and also by the impalpable past occurrence of a memorable event of public relevance. Beyond the constraints imposed by the government, it would be senseless, for example, to consider the couple of hectares of meadow within Rome occupied by the Circus Maximus (Figure 1) as any other equivalent piece of land. Some past events occurred in given areas just because of the characteristics of their soils (i.e. duels and battles on soils selected just because of their high or poor bearing capacity), which should therefore be acknowledged and preserved. In other cases, urban soils are the result of efforts aimed at making them suitable for specific purposes, such as the creation of historical gardens (Delgado et al., 2007). Such efforts, including the provenance of the soil material, where this is allochthonous, should be acknowledged in classifying those soils, just because of their value as historical memories (Beach et al., 2015).

Additional facets may deal not with soil *per se*, but with the conditions affecting its ecology and fertility, such as, for example, the extent of solar radiation it receives all year long; Italian legislation includes a *shadow* tax that relates to the shape of buildings and their interference on solar irradiation of adjacent soils (Gazzetta Ufficiale, 1997). Also, proxy indicators of ongoing peri-urbanization processes based, for instance, on a differentiation into displaced-urbanization, ex-urbanization, anti-urbanization and hidden-urbanization could be used as facets for our purpose (Zasada et al., 2011).

The organization of soil information – including that provided by canonical classification – in a facet repository undoubtedly helps in overcoming the problems of spatial data resolution highlighted by Schmit et al. (2006). When interrogated, a faceted system for urban soils would produce a list of soils that are, for example, silty, acid, not contaminated by heavy metals, with a tolerable content of hydrocarbons, smaller than 100 m^2 and with a rectangular shape, flat, surrounded by buildings on just two sides, state-owned, insignificant from the aesthetical and historical points of view but socially and ecologically valuable. The result would be meaningful in terms of urban planning and highly useful for easily intercepting potential land uses. The organization of soil data in facets would make it easy to create thematic maps for individual properties (e.g. land metrics, specific pollution, property, economic value, mapping error estimates ...), regardless of data standard format and complete availability.

A faceted system would be particularly convenient where the information about soils is missing or scattered, as frequently happens in urban settings (Figures 2 and 3). The system can in fact work with any amount of information and progressively host new data, when they are, for example, obtained or imported from other city services (e.g. the cadastre may feed its data into the system while the environment department is still making investigations). In fact, it is becoming possible and desirable to update soil map information (Sun et al., 2015). The FC system is also flexible in accepting changes in the limit values of the classes, as when the legal thresholds for contamination are changed (Table 2). This implies advantages for the local administration, which would deal with a much more understandable and easy-to-apply system. Armentano et al. (2014) have in fact reported that the use of a faceted system allows a search engine to be devised that produces user-friendly presentations for non-expert users.

It has been postulated that a post-coordination approach, i.e. mixing different properties – facets – in an unusual way, may allow new associations of elements to be discovered (Elliott et al., 2000; Kwasnik, 1999), hence generating new knowledge. A faceted system would be highly appropriate for following the evolution of open data sets, integrating territorial systems with the concept of learning territorial networks (Finka and Kluvánková, 2015). Environmental data sharing, remote sensing, and visualization tools and practices can also support next-generation ecosystem service modelling (Bagstad et al., 2013). Archives that contain a huge mass of soil information in a digital format are available worldwide, but a combined exploration of this large collection of soil data is hindered by their multivariate nature (Beaudette et al., 2013) and a faceted system would help in exploiting the data. Crowd-mapping, a combination of social activism, citizen journalism and geospatial information, is rapidly growing and urban soil mapping should benefit from it. This approach, which was first applied to arable/natural soils, is now expanding towards urban areas. Combining crowd-mapping and a faceted system of nomenclature could be a winning strategy to improve the knowledge of urban soils.

3. Conclusions

Current systems of soil classification show some limitations in accounting for what is commonly needed for the use and management of urban soils, mostly because they were built on a genetic base and for agricultural purposes. Temporal and spatial variability of soil in the urban context is so high and unpredictable compared to agricultural or natural soils that systematization and transmission of the information on urban soils becomes an overwhelming task. This is the main reason why unsealed urban soils are currently mapped as indistinct areas included in the patches representing urban settlements.

A faceted system of categorization based on both tangible and immaterial features and values could more adequately account for the complexity of the world of urban soils than classic soil classifications. In addition, it would show the flexibility necessary to progressively accommodate the flow of scattered, rapidly changing, sometimes incomplete, data that are being continuously collected. If constantly updated once new information is provided, such a system of classification of urban soils would be a pivotal tool for urban and peri-urban landscape planning and management.

4. References

Abrahams, P.W., 2006. Soil, geography and human disease: A critical review of the importance of medical cartography. Progr. Phys. Geogr. 30, 490–512.

Adhikari K., Hartemink A.E., 2016. Linking soils to ecosystem services – A global review. Geoderma 262, 101–111.

Ajmone-Marsan, F., Biasioli, M., 2010. Trace elements in soils of urban areas. Water Air Soil Poll. 213, 121–143.

Andersson, M., Ottesen, R.T., Langedal, M., 2010. Geochemistry of urban surface soils – Monitoring in Trondheim, Norway. Geoderma 156, 112–118.

Anonymous, 2010. Cities: The century of the city. Nature 467, 900–901.

Aparin, B.F., Sukhacheva, E.Yu., 2014. Principles of soil mapping of a megalopolis with St. Petersburg as an example. Eurasian Soil Sci. 47, 650–661.

Armentano, M.G., Godoy, D., Campo, M., Amandi, A., 2014. NLP-based faceted search: Experience in the development of a science and technology search engine. Expert Syst. Appl. 41, 2886–2896.

Arnold, R.W., 2006. Concepts of soils. In: Certini, G., Scalenghe, R., (Eds.), Soils: Basic Concepts and Future Challenges. Cambridge University Press, UK, pp. 1–10.

Bagstad, K.J., Semmen, D.J., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosys. Serv. 5, e27–e29.

Bartie, P., Reitsma, F., Kingham, S., Mills, S., 2010. Advancing visibility modelling algorithms for urban environments. Comput. Environ. Urban Syst. 34, 518–531.

Beach, T., Luzzadder-Beach, S., Cook, D., Dunning, N., Kennett, D.J., Krause, S., Terry, R., Trein, D., Valdez, F., 2015. Ancient Maya impacts on the Earth's surface: An Early Anthropocene analog? Quatern. Sci. Rev. 124, 1–30.

Beaudette, D.E., Roudier, P., O'Geen, A.T., 2013. Algorithms for quantitative pedology: A toolkit for soil scientists. Comput. Geosci. 52, 258–268.

Biasioli, M., Barberis, R., Ajmone-Marsan, F., 2006. The influence of a large city on some soil properties and metals content. Sci. Tot. Environ. 356, 154–164.

Boaga, J., 2013. An efficient tool for cultural heritage seismic soil classification: Frequency time analysis method in Venice historical center and its lagoon (Italy). Geosci. J. 17, 301−311.

Borgogno-Mondino, E., Fabietti, G., Ajmone-Marsan, F., 2015. Soil quality and landscape metrics as driving factors in a multi-criteria GIS procedure for peri-urban land use planning. Urban For. Urban Green. 14, 743−750.

Bouma, J., Droogers, P., 2007. Translating soil science into environmental policy: A case study on implementing the EU soil protection strategy in The Netherlands. Env. Sci. Pol. 10, 454–463.

Brander, L.M., Koetse, M.J., 2011. The value of urban open space: Meta-analyses of contingent valuation and hedonic pricing results. J. Environ. Manage. 92, 2763–2773.

Brevik, E.C., Calzolari, C., Miller, B.A., Pereira, P., Kabala, C., Baumgarten, A., Jordán, A., 2015. Soil mapping, classification, and pedologic modeling: History and future directions. Geoderma (in press) doi>10.1016/j.geoderma.2015.05.017

Broughton, V., 2006. The need for a faceted classification as the basis of all methods of information retrieval. Aslib Proceed. 58, 49–72.

Casalegno, S., Inger, R., DeSilvey, C., Gaston, K.J., 2013. Spatial covariance between aesthetic value and other ecosystem services. PLoS ONE 8, e68437 doi>10.1371/journal.pone.0068437

Cattle, J.A., McBratney, A.B., Minasny, B., 2002. Kriging method evaluation for assessing the spatial distribution of urban soil lead contamination. J. Environ. Qual. 31, 1576–1588.

Chamberlain, B.C., Meitner, M.J., 2013. A route-based visibility analysis for landscape management. Land. Urban Plann. 111, 13–24.

Chatterjee, K, Choudhury, D., 2013. Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis. Nat. Hazards 69, 2057–2082.

Commission of the European Communities. 2006. Thematic Strategy for Soil Protection. COM(2006)231 final.

Costa, C., Reis, A.P., Ferreira da Silva, E., Rocha, F., Patinha, C., Dias, A.C., Sequeira, C., Terroso, D., 2012. Assessing the control exerted by soil mineralogy in the fixation of potentially harmful elements in the urban soils of Lisbon, Portugal. Environ. Earth Sci. 65, 1133–1145.

Curran-Cournane, F., Vaughan, M., Memon, A., Fredrickson, C., 2014. Trade-offs between high-class land and development: Recent and future pressures on Auckland's valuable soil resources. Land Use Pol. 39, 146–154.

Delgado R., Martín-García, J.M., Calero, J., Casares-Porcel, M., Tito-Rojo, J., Delgado G., 2007. The historic man-made soils of the Generalife garden (La Alhambra, Granada, Spain). Eur. J. Soil Sci. 58, 215–228.

Deng, X., 2007. New trends in digital terrain analysis: Landform definition, representation, and classification. Progr. Phys. Geogr. 31, 405–419.

Dudal, R., Deckers, J., Van Orshoven, J., Van Ranst, E. (2005). Soil survey in Belgium and its applications. In: Jones, R.J.A., Houšková, B., Bullock, P., Montanarella, L. (Eds.), Soil Resources of Europe, 2nd edition. European Soil Bureau Research Report No. 9, EUR 20559 EN. Office for Official Publications of the European Communities, Luxembourg.

Elliott, S., Decker, E., Smith, F.A., Blake, D.R., Simpson, I.J., Sherwood Rowland, F., 2000. Cities in the earth system. Env. Sci. Pol. 3, 157–160.

Ellis, E.C., 2011. Anthropogenic transformation of the terrestrial biosphere. Phil. Trans. Royal Soc. A 369, 1010–1035.

European Environment Agency, 2011. Landscape Fragmentation in Europe. Report No 2/2011. EEA, Copenhagen, DK.

Finka, M., Kluvánková, T., 2015. Managing complexity of urban systems: A polycentric approach. Land Use Pol. 42, 602–608.

Fitzpatrick, E.A, 1967. Soil nomenclature and classification. Geoderma 1, 91–105.

Frické, M.H., 2013. Facets: Ersatz, resource and tag. Information Research, 18(3) paper C25. Downloadable at: http://files.eric.ed.gov/fulltext/EJ1044660.pdf

Gardi, C., Jeffery, S., Saltelli, A., 2013. An estimate of potential threat levels to soil biodiversity in EU. Glob. Change Biol. 19, 1538–1548.

Gazzetta Ufficiale, 1997. Decreto Legislativo 15 dicembre 1997, n. 446. Gazzetta Ufficiale n. 298 del 23 dicembre 1997. Repubblica Italiana, Roma, IT.

Giusti, L., 2011. Heavy metals in urban soils of Bristol (UK). Initial screening for contaminated land. J. Soil Sedim. 11, 1385–1398.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs J.M., 2008. Global change and the ecology of cities. Science 319, 756–760.

Groome, D., 1990. Green corridors – A discussion of a planning concept. Land Urban Plann. 19, 383–387.

Guillén, M.T., Delgado, J., Albanese, S., Nieto, J.M., Lima, A., De Vivo, B., 2012. Heavy metals fractionation and multivariate statistical techniques to evaluate the environmental risk in soils of Huelva Township (SW Iberian Peninsula). J. Geochem. Explor. 119–120, 32–43.

Han, S.S., 2010. Urban expansion in contemporary China: What can we learn from a small town? Land Use Pol. 27, 780–787.

Hartemink, A.E., Krasilnikov, P., Bockheim, J.G., 2013. Soil maps of the world. Geoderma 207–208, 256–267.

Heuvelink, G.B.M., Webster, R., 2001. Modelling soil variation: Past, present, and future. Geoderma 100, 269–301.

Hjørland, B. 2013a. Theories of Knowledge Organization—Theories of Knowledge. Knowledge Organization. 40, 169-181.

Hjørland, B., 2013b. Facet analysis: The logical approach to knowledge organization. Inform. Process. Manage. 49, 545–557.

Hollis, J.M., 1991. The classification of soils in urban areas. In: Bullock, P., Gregory, PJ, (Eds.), Soils in the Urban Environment. Blackwell Scientific Publications, Oxford, UK, pp. 5–27.

Holmgren, G.G.S., 1988. The point representation of soil. Soil Sci. Soc. Am. J. 52: 712–716.

Hou, D., Al-Tabbaa, A., 2014 Sustainability: A new imperative in contaminated land remediation. Environ. Sci. Pol., 39: 25–34.

Hu, S., Cheng, Q., Wang, L., Xu, D., 2013. Modeling land price distribution using multifractal IDW interpolation and fractal filtering method. Land. Urban Plann. 110, 25–35.

Ibáñez, J.J., Zinck, J.A., Dazzi, C., 2013. Soil geography and diversity of the European biogeographical regions. Geoderma 192, 142–153.

IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jeffery, S., Gardi, C., Jones, A., Montanarella, L., Marmo, L., Miko, L., Ritz, K., Peres, G., Römbke, J., van der Putten, W.H. (eds.), 2010. European Atlas of Soil Biodiversity. European Commission, Publications Office of the European Union, Luxembourg.

Kabisch, N., 2015. Ecosystem service implementation and governance challenges in urban green space planning –The case of Berlin, Germany. Land Use Pol. 42, 557–567.

Kara, C., Doratli, N., 2012. Application of GIS/AHP in siting sanitary landfill: A case study in Northern Cyprus. Waste Manage. Res. 30, 966–980.

Kasanko, M., Barredo, J.I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V., Brezger, A., 2006. Are European cities becoming dispersed? A comparative analysis of 15 European urban areas. Land. Urban Plann. 77, 111–130.

Kent, M., 2009. Biogeography and landscape ecology: The way forward – Gradients and graph theory. Progr. Phys. Geogr. 33, 424–436.

Kwasnik, B.H., 1999. The role of classification in knowledge representation and discovery. Libr. Trends 48, 22–47.

Kwasnik, B.H., 2002. Commercial websites and the use of classification schemes: The case of amazon.com. In: Lopez-Huertas, M.J., (Ed.), Challenges in Knowledge Representation and Organization for the 21st Century: Integration of Knowledge Across Boundaries (pp. 279–285). Proceedings of the Seventh International ISKO Conference. Ergon, Würzburg, DE.

Lebedeva, I.I., Gerasimova, M.I., 2011. Possibilities of including the taxonomy of soils and parent materials of Moscow City into the classification system of the soils of Russia. Eur. Soil Sci. 44, 572–575.

Lehmann, A., Stahr, K., 2007. Nature and significance of anthropogenic urban soils. J. Soil Sedim. 7, 247–260.

Litt, J.S., Soobader, M.-J., Turbin, M.S., Hale, J.W., Buchenau, M., Marshall, J.A., 2011. The influence of social involvement, neighborhood aesthetics, and community garden participation on fruit and vegetable consumption. Am. J. Public Health 101, 1466–1473.

Lorenz, K., Lal, R., 2009. Biogeochemical C and N cycles in urban soils. Environ. Intern. 35, 1–8.

Lundy, L., Wade, R., 2011. Integrating sciences to sustain urban ecosystem services. Progr. Phys. Geogr. 35, 653–669.

Lüscher, G., Schneider, M.K., Turnbull, L.A., Arndorfer, M., Bailey, D., Herzog, F., Pointereau, P., Richner, N., Jeanneret, P., 2014. Appropriate metrics to inform farmers about species diversity. Env. Sci. Pol. 41, 52–62.

McGarigal, K., Marks, B.J., 1995. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. General Technical Report PNW-GTR-351. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA

Maruani, T., Amit-Cohen, I., 2013. Marketing landscapes: The use of landscape values in advertisements of development projects. Land. Urban Plann. 114, 92–101.

Moeinaddini, M., Khorasani, N., Danehkar, A., Darvishsefat, A.A., Zienalyan, M., 2010. Siting MSW landfill using weighted linear combination and analytical hierarchy process (AHP) methodology in GIS environment (case study: Karaj). Waste Manage. 30, 912–920.

Morillo, E., Romero, A.S., Maqueda, C., Madrid, L., Ajmone-Marsan, F., Grčman, H., Davidson, C.M., Hursthouse, A.S., Villaverde, J., 2007. Soil pollution by PAHs in urban soils: A comparison of three European cities. J. Environ. Monit. 9, 1001–1008.

Natural Environment Research Council, 2013. mySoil. Version 2.0. Free app in English ©NERC, UK.

Nehls, T., Rokia, S., Mekiffer, B., Schwartz, C., Wessolek, G., 2013. Contribution of bricks to urban soil properties. J. Soil Sedim. 13, 575–584.

Niedertscheider, M., Erb, K., 2014. Land system change in Italy from 1884 to 2007: Analysing the North–South divergence on the basis of an integrated indicator framework. Land Use Pol. 39, 366–375.

Norra, S., Stüben, D., 2003. Urban soils. J. Soil Sedim. 3, 230–233.

Nuissl, H., Haase, D., Lanzendorf, M., Wittmerd, H., 2009. Environmental impact assessment of urban land use transitions – A context-sensitive approach. Land Use Pol. 26, 414–424.

Panduro, T.E., Veie, K.L., 2013. Classification and valuation of urban green spaces – A hedonic house price valuation. Land. Urban Plann. 120, 119–128.

Perugini, S., 2010. Supporting multiple paths to objects in information hierarchies: Faceted classification, faceted search, and symbolic links. Inf. Proc. Manage. 46, 22–43.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Boone, C.G., Groffman, P.M., Irwin, E., Kaushal, S.S., Marshall, V., McGrath, B.P., Nilon, C.H., Pouyat, R.V., Szlavecz, K., Troy, A., Warren, P., 2011. Urban ecological systems: Scientific foundations and a decade of progress. J. Environ. Manage. 92, 331–362.

Puertas, O.L., Henríquez, C., Meza, F.J., 2014. Assessing spatial dynamics of urban growth using an integrated land use model. Application in Santiago Metropolitan Area, 2010–2045. Land Use Pol. 38, 415–425.

Qiao, M., Chao Cai, C., Huang, Y., Liu, Y., Lin, A., Zheng, Y., 2011. Characterization of soil heavy metal contamination and potential health risk in metropolitan region of northern China. Environ. Monit. Assess. 172, 353–365.

Qin, J., Zhou, X., Sun, C., Leng, H., Lian, Z., 2013. Influence of green spaces on environmental satisfaction and physiological status of urban residents. Urban For. Urban Green. 12, 490–497.

Ranganathan, S.R., 1967. Prolegomena to Library Classification, 2nd ed. 1957, 3rd ed. 1967. London: Asia Publishing House. http://hdl.handle.net/10150/106370

Rossiter, D.G., 2007. Classification of urban and industrial soils in the World Reference Base for Soil Resources. J. Soils Sedim. 7, 96–100.

Sanchez, P.A., Couto, W., Buol, S.W., 1982. The fertility capability soil classification system: Interpretation, applicability and modification. Geoderma 27, 283–309.

Sanchez, P.A., Palm, C.A., Buol, S.W., 2003. Fertility capability soil classification: A tool to help assess soil quality in the tropics. Geoderma 114, 157–185.

Sanchez, P.A., Ahamed, S., Carré, F., Hartemink, A.E., Hempel, J., Huising, J., Lagacherie, P., McBratney, A.B., McKenzie, N.J., de Lourdes Mendonça-Santos, M., Minasny, B., Montanarella, L., Okoth, P., Palm, C.A., Sachs, J.D., Shepherd, K.D., Vågen, T.G., Vanlauwe, B., Walsh, M.G., Winowiecki, L.A., Zhang, G.L., 2009. Digital soil map of the world. Science 325, 680–681.

Scalenghe, R., Ajmone-Marsan, F., 2009. The anthropogenic sealing of soils in urban areas. Land. Urban Plann. 90, 1–10.

Scalenghe, R., Malucelli, F., Fabrizio, U., Perazzone, L., Filippi, N., Edwards, A.C., 2011. Influence of 150 years of land use on anthropogenic and natural carbon stocks in Emilia-Romagna Region (Italy). Environ. Sci. Techn. 45, 5112–5117.

Scharenbroch, B.C., Lloyd, J.E., Johnson-Maynard, J.L., 2005. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49, 283–296.

Schmidt, R., Daeumlich, D., Reuter, H.I., 2004. From point over regions to the landscape – Spatial generalization in the soil landscape research. Arch. Agron. Soil Sci. 50, 241–257.

Schmit, C., Rounsevell, M.D.A., La Jeunesse, I., 2006. The limitations of spatial land use data in environmental analysis. Environ. Sci. Pol. 6, 174–188.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D., 2002. Field Book for Describing and Sampling Soils. Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schulte, R.P.O., Creamer, R.E., Donnellan, T., Farrelly, N., Fealy, R., O’Donoghue, C., Daire O’hUallachain, D., 2014. Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environ. Sci. Pol. 38, 45–58.

Schwarz, K., Pickett, S.T.A., Lathrop, R.G., Weathers, K.C., Pouyat, R.V., Cadenasso, M.L., 2012. The effects of the urban built environment on the spatial distribution of lead in residential soils. Environ. Pollut. 163, 32–39.

Semenza, J.C., March, T.L., 2009. An urban community-based intervention to advance social interactions. Environ. Behav. 41, 22–42.

Slavic, A., 2008. Faceted classification: Management and use. Axiomathes 18, 257–271.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service. Washington, DC.

Sun, X.-L., Wu, Y.-J., Lou, Y.-L., Wang, H.-L., Zhang, C., Zhao, Y.-G., Zhang, G.-L., 2015. Updating digital soil maps with new data: A case study of soil organic matter in Jiangsu, China. Eur. J. Soil Sci. doi>10.1111/ejss.12295

Tzoulas, K., James, P., 2010. Making biodiversity measures accessible to non-specialists: An innovative method for rapid assessment of urban biodiversity. Urban Ecosys. 13, 113–127.

United Nations, Department of Economic and Social Affairs, Population Division, 2014. World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

Vasenev, V.I., Stoorvogel, J.J., Vasenev, I.I., Valentini, R., 2014. How to map soil organic carbon stocks in highly urbanized regions? Geoderma 226–227, 103–115.

Vickery, B.C., 1960. Faceted Classification: A Guide to Construction and Use of Special Schemes. Aslib, London, UK.

Vickery, B.C., 2008. Faceted classification for the web. Axiomathes 18, 145–160.

Vilček, J., Bujnovský, R., 2014. Soil environmental index for Slovak agricultural land. Pedosphere 24, 137–144.

Wang, X-T., Miao, Y., Zhang, Y., Li, Y-C., Wu, M-H., Yu, G., 2013. Polycyclic aromatic hydrocarbons (PAHs) in urban soils of the megacity Shanghai: Occurrence, source apportionment and potential human health risk. Sci. Tot. Environ. 447, 80–89.

Zasada, I., Fertner, C., Piorr, A., Nielsen, T.S., 2011. Peri-urbanisation and multifunctional adaptation of agriculture around Copenhagen. Dan. J. Geogr. 111, 59–72.

Table captions:

Table 1. Soil properties that are currently observed and annotated in the field for conventional soil classification (modified from Schoeneberger et al., 2002)

Table 2. A faceted classification as employed by Amazon.com and which could be used for urban soils

Amazon numbers brand, price, and seller as individual facets. The first two columns on the left show a search made on Amazon.com; the first one in particular shows the results from a search using the keyword 'computer'. Amazon also have facets that are specific to the current result set, which are shown in the second column where the results of the first column are filtered using the word 'Windows 8' (in parentheses are the number of items found). A plausible example of search through an urban soil database organized by facets using the keyword 'Urban Soil' is the one reported in the third column, which in the fourth one is filtered by the keyword 'Ownership'.

Figure captions:

Figure 1: a–e) examples of soils in an urban and peri-urban environment; g) the ancient Roman chariot racing stadium *Circus Maximus* (photo: Ministero dell'Ambiente e della Tutela del Territorio e del Mare; location 41°53′9.26″N, 12°29′8.53″E) h) a road junction encompasses soils that are subtracted for any other use (photo: Google Earth; location 45°01'20"N; 7°35'52"E). (The expression 'peri-urban', first used in France [and Switzerland], describes spaces shaped by the urbanization between the city and the rural area, in the urban fringe. Peri-urban both in a social [e.g. lifestyle] and in a physical [e.g. land use change] sense).

Figure 2. A statistically representative sampling of urban soils appears to be impossible. A grid is superposed on a city map in order to plan a systematic survey. However, only the areas in green are open soils and they would not provide a statistically sound representation of soil spatial variability.

Figure 3: Facets vs canonical soil categorizations. In a non-urban context (a): soil is sampled, then the data of all concerned property useful for its classification is spatialized and a soil scientist can draw a soil map. From these maps a land planner or any stakeholder can infer soil properties of non-observed points from their taxonomic classification. In an urban context (b): the city (dark area) does not allow for a representative sampling of soils, the spatialization of data can be made only in open soil areas. Within the urban area, there is not sufficient information to be able to assign a proper soil

classification to an area, only an individual point can be classified, if it is observed directly. It is not possible to extract any plausible information from non-observed points. In an urban+peri-urban context (c): the city (dark area) and areas that have been, e.g. brownfields, or will become urban (grey areas) do not allow a mapping of the soils due to the unfeasibility of spatialization punctual taxonomic categorization. In an urban+peri-urban context (d): the city (dark area) and areas that have been, e.g. brownfields, or will become urban (grey areas) are continually being dug/surveyed/explored for different purposes. The number of observations is very high; the characteristics of the collected data are heterogeneous and independent from a formal framework of any existing classification systems. The organization of these data in facets makes it possible to create thematic maps for individual properties (e.g., land metrics, specific pollution, property, economic value ...), depending on the data availability only.