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An integrated evaluation of soil resource depletion from diachronic settlement maps and soil cartography in peri-urban Rome, Italy

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ABSTRACT

The present study contributes to the multi-temporal analysis of soil resource depletion in the large Mediterranean urban region of Rome (central Italy) based on the integration of high-resolution building density maps (1919–2001) with a set of indicators derived from soil maps and describing soil properties and susceptibility to various degradation processes. The recent growth of Rome is characterised by intense expansion of built-up areas around the inner city and has preferentially consumed soils with an overall high quality and low sensitivity to degradation. Multivariate analyses confirm that urban expansion in the study area impacted soils with different characteristics in a spatially-asymmetric way and identify two main dimensions of soil depletion based on specific soil attributes and the absence of soil degradation processes. Diachronic studies quantifying soil resource depletion resulting from urban expansion, as is illustrated in this paper, are useful tools to develop joint measures aimed at containing urban sprawl and preserving soil resources.

1. Introduction

A progressively larger proportion of wild and rural areas worldwide are being converted to residential, commercial and industrial settlements as well as transport infrastructures (Pickett et al., 2001; Xiao et al., 2013; Zhang et al., 2007). Peri-urban landscapes have experienced drastic land-use changes in recent decades as a result of population growth, rapid expansion of tourism, industrial development and the intensification of agriculture in lowlands, forest fires, overgrazing and land abandonment in rural areas (European Commission, 2006; Kosmas et al., 1999; Salvati and Bajocco, 2011; Zavala and Burkey, 1997). Urbanisation is considered one of the most rapid drivers of change and causes habitat fragmentation, the abandonment of agricultural land and loss in biodiversity, all of which indirectly affect soils (Eswaran et al., 1997; Karlen et al., 2003; Scalenghe et al., 2012). While the impact of urbanisation on landscape structure and composition has been explored for different socioeconomic contexts (e.g., Amundson et al., 2003; Herold et al., 2003, 2005), soil depletion due to urban (both planned and spontaneous) growth has been poorly monitored on a regional and local scale (Salvati, 2013). At the same time, the impact of soil degradation on human welfare and the global environment presents a major challenge (Arshad and Coen, 1992).

Soil is a vital, limited and non-renewable resource that plays an essential role in ecosystem services such as biological productivity, water purification and carbon cycling, and it has a significant potential to remove gases that are responsible for climate change from the atmosphere (European Environment Agency, Joint Research Centre, 2012; Lal, 2004; Scalenghe et al., 2012). The ability of soil to perform any of its functions depends on its physical, chemical and biological characteristics (Bouma et al., 1998; Karlen et al., 2001) which are conditioned by natural and anthropogenic factors (Eswaran et al., 1997; Karlen et al., 2001). Humans are among the most influential agents and directly or indirectly impact the performance characteristics of soil, thus limiting or enhancing its productive capacity (Amundson et al., 2003). Moreover, soils show a multifaceted relationship with natural resource management, in part because soils are inherently variable and susceptible to multiple uses for the benefit of human beings (e.g., Brevik, 2009, 2013; Sposito and Zabel, 2003).

Positive feedback dynamics between growing population and massive urbanisation, land cover, and climate change have led to a rapid loss in the capacity of soils to deliver essential ecosystem services (Pickett et al., 2001). This was reflected in a significant decline in soil quality that occurred worldwide through adverse changes in its physical, chemical, and biological attributes (Schjønning et al., 2004). These changes are not easily reversible, representing major development costs. Monitoring soil properties and overall quality is thus an essential step for preventing degradation processes frequently associated to intensive or inappropriate management of the soil resource (Collins et al., 2000). There have been many definitions of soil quality being primarily linked to the concepts of 'fitness for use' and 'the capacity of a soil to function' (Sojka and Upchurch, 1999). These concepts refer soil quality to the ability of the soil to

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perform the functions necessary for its intended use. Karlen et al. (1997) give a more comprehensive definition indicating soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". This definition emphasizes the value of the soil to perform specific functions within ecosystem boundaries.

As a result, increasing attention has been paid on the exploration of soil variables, which could be readily used as soil indicators (Arshad and Coen, 1992). These indicators could be divided into different soil properties and include, among others, soil depth, organic matter, available water-holding capacity, hydraulic conductivity, aggregate stability, nutrient availability/retention capacity, and, where appropriate, electrical conductivity and exchangeable sodium (Schloter et al., 2003). Justification for selecting these attributes, their measurement and critical limits for soil monitoring were provided in Karlen et al. (1997, 2001).

Unfortunately, our ability to assess soil quality, and more generally, soil resources is complicated by many processes and their interactions in time and space (Sojka and Upchurch, 1999). To operationalize multifaceted soil concepts through reliable indicators, which can be disseminated through non-technical, stakeholders like planners, politicians, non-farmer land-users and interested citizens at large, is still an intriguing and crucial issue in soil science (Bouma, 2001a). It is not usually possible to directly measure the rate of soil processes; instead they can be inferred by measuring specific soil attributes that are indicative of these rates (Salvati, 2013). The traditional and more comprehensive definitions of soil quality should be therefore fine tuned with the difficulties to collect reliable soil data covering large areas at an enough detailed spatial resolution (Marzaioli et al., 2010). Multivariate analysis was largely used to overcome data restriction with the aim to explore, integrate and, possibly, model the combined effects of several soil properties and processes (e.g. Recio-Vazquez et al., 2014).

Finally, the exercise of soil quality evaluation involves explicit judgement of which soil conditions will fit the sustainability expressions in this definition. This link between soil quality and sustainability is so very important because soil quality should not remain an abstract concept but rather something to be strived for by management (Bouma, 2001a). Mainly for this reason, soil monitoring and preservation initiatives are critical for ensuring environmental quality. Evaluating soils based on a quantification of their characteristics and properties, suitability for agriculture and forestry, services provided to the environment and capacity to respond to biotic and a-biotic stresses is particularly difficult (Scalenghe et al., 2012) and monitoring approaches may benefit from integrated methodologies to evaluate soil resources in both physical and economic terms (Brevik, 2009; Collins et al., 2000; Schloter et al., 2003; Sposito and Zabel, 2003).

In the Mediterranean region, the loss of soil quality and the depletion of soil resources are of special concern due to the particular fragility of these ecosystems (Kosmas et al., 1999). Permanent sealing of land for housing, roads or other construction work is a crucial degradation factor since it causes irreversible changes in the natural condition of the permeable layer and results in a significant loss of soil resources (European Environment Agency, Joint Research Centre, 2012; Munafò et al., 2010; Scalenghe and Ajmone Marsan, 2009). Soils removed for sealing are difficult to recuperate because of the loss of constituent elements of the soil systems, including microorganisms, mesofauna and flora (García et al., 2014).

Because of socioeconomic development, recent challenges in southern European urban areas include a drastic low-density sprawl coupled with impressive deconcentration processes in inner cities. Since the early 1980s, several Mediterranean cities underwent a rapid transition from compact forms to a more dispersed morphology (Catalàn et al., 2008; Chorianopoulos et al., 2010; Paul and Tonts, 2005; Salvati et al., 2012). Consequently, a drastic increase in soil sealing has been found in recent years, especially in more accessible, peri-urban areas (European Commission, 2006; Kasanko et al., 2006; Zavala and Burkey, 1997).

Socioeconomic challenges may influence soil resource depletion via conversion of natural and agricultural land to urban uses, and it has been hypothesised that the expansion of compact settlements primarily consumes low-quality soils and degraded landscapes (e.g., pastures, abandoned fields and low-intensity agricultural areas) that are located on the fringes of cities (Salvati et al., 2012). In contrast, an increasing proportion of high-quality rural and natural areas farther away from inner cities may undergo huge land cover changes and habitat fragmentation because of dispersed settlement expansion (Salvati and Sabbi, 2011). Based on a diachronic study examining the last fifty years and concentrating on a dense urban region in the Mediterranean, Salvati (2013) demonstrated that land-taking linked to various patterns of urban expansion may consume soils with different physical properties over time. Using a regional approach, Ceccarelli et al. (2014) identified soils with high crop suitability as the most threatened by dispersed urbanisation in northern Italy. These findings are in line with what was reported by Zhang et al. (2007), Xiao et al. (2013) and García et al. (2014). It was also hypothesised that sealing processes cause an increased risk of land degradation (Salvati et al., 2012) and desertification (Barbero-Sierra et al., 2013; see also Portnov and Safriel, 2004).

Increasing concerns for soil consumption on both the continental and country levels justify permanent monitoring and further research to improve the sustainable management of peri-urban soils (Salvati et al., 2012). Unfortunately, recent studies on urbanisation-driven land consumption (García et al., 2014; Munafò et al., 2010; Salvati, 2013; Zhang et al., 2007) mainly focused on specific soil variables or qualities (e.g., suitability to agriculture), but a more in-depth and integrated approach is required (e.g., McBratney et al., 2014), possibly one that is based on a multivariate set of indicators integrating soil properties and soil degradation processes (see, as instance, Recio-Vazquez et al., 2014). Subjected to suitable spatial operations and the availability of data, the derived built-up layers can be overlaid with diachronic building maps and reveal the spatial patterns of soil sealing. Multivariate approaches coupled with more traditional statistical techniques have proven capable of identifying latent soil-landscape patterns (Xiao et al., 2013) that would also be useful from a land management perspective (Salvati et al., 2012).

Based on these premises, the objective of the present study is to introduce an integrated framework to assess soil resource depletion driven by sealing processes on a detailed spatial resolution. Soil characteristics were described using twelve indicators classified in two categories: (i) selected soil properties and (ii) exposure to different soil degradation processes. The innovative contribution of this study is in the consideration of both traditional indicators of soil properties and proxies for selected soil degradation processes in a multivariate approach indicating what type of soil is consumed by urbanisation. The assessment benefits from the integration of long-term diachronic building maps covering more than 80 years of urban growth and soil geo-databases. A large area experiencing different phases of urban expansion in Italy was chosen as a representative case study with the aim of understanding how land consumption and soil characteristics are related in time and space.

2. Methods

2.1. Study area

The study area covers Rome's province, which has a total surface area of 5355 km^2 and is characterised by a complex topography consisting of 70% lowlands and 30% uplands (Fig. 1). The main morphological formations are the Simbruini mountains (maximum elevation 1820 m above sea level) in the Apennine region, whereas the lowlands (the so called "Agro Romano") are located over the alluvial plain of the