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Multitemporal mapping of peri-urban carbon stocks and soil sealing from satellite data

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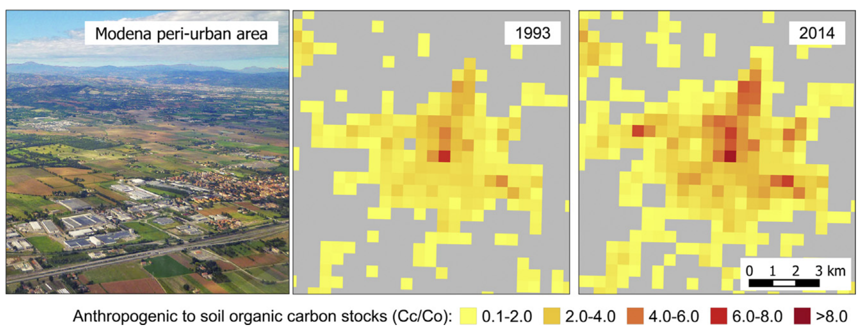
HIGHLIGHTS

- Remote sensing can be used to map peri-urban C stocks in reliable way ($R^2 > 0.6$).
- Quantitative analysis of sealing dynamics is possible combining peri-urban C stocks.
- Under severe sealing, anthropogenic C stocks can equate organic C stored in soils.
- When prime farmland soils occupy <60% of an area, preservation is hard.
- Satellites can provide monitoring tools in aid of landscape conservation planning.

GRAPHICAL ABSTRACT



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ABSTRACT

Peri-urbanisation is the expansion of compact urban areas towards low-density settlements. This phenomenon directly challenges the agricultural landscape multifunctionality, including its carbon (C) storage capacity. Using satellite data, we mapped peri-urban C stocks in soil and built-up surfaces over three areas from 1993 to 2014 in the Emilia-Romagna region, Italy: a thinly populated area around Piacenza, an intermediate-density area covering the Reggio Emilia-Modena conurbation and a densely anthropized area developing along the coast of Rimini. Satellite-derived maps enabled the quantitative analysis of spatial and temporal features of urban growth and soil sealing, expressed as the ratio between C in built-up land and organic C in soils (Cc/Co). The three areas show substantial differences in C stock balance and soil sealing evolution. In Piacenza (Cc/Co = 0.07 in 1993), although questioned by late industrial expansion and connected residential sprawl (Cc/Co growth by 38%), most of the new urbanisation spared the best rural soils. The Reggio Emilia-Modena conurbation, driven by the polycentricism of the area and the heterogeneity of economic sectors (Cc/Co rising from 0.08 to 0.14 from 1993 to 2014), balances sprawl and densification. Rimini, severely sealed since the 1960s (Cc/Co = 0.23 in 1993), densifies its existing settlements and develops an industrial expansion of the hinterland, with Cc/Co growth accelerating from +15% before 2003 to +36% for the last decade.

1. Introduction

Urbanisation is a complex progression from rural into urban land use and lifestyle, driven by population growth, socio-economic and cultural development, environmental factors, infrastructure and landscape planning (Low Choy and Sutherland, 2008; Mallinis et al., 2014; Mann et al.,

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2014; Serra and Pinho, 2011). Peri-urban fringes are composite areas attracting population from urban centres; as this, their evolution no longer depends on the urban areas this population comes from (Gospodini, 2006; Serra and Pinho, 2011). A variety of approaches have been proposed to assess urban expansion patterns, ranging from using landscape metrics (*e.g.* Borgogno-Mondino et al., 2015) and socio-economic indicators (*e.g.* Huang et al., 2007) to more specific ones, such as historical evolution biography (Palang et al., 2011) or non-reductionist analyses presenting land change narratives along with quantitative models (McCauley et al., 2015).

In Europe, peri-urbanisation aggravates soil sealing, which is one of the major causes of soil degradation, heavily disturbing agricultural land and biodiversity and intensifying the risk of flooding (Scalenghe and Ajmone Marsan, 2009; Ungaro et al., 2014). According to the European Commission, limiting soil sealing should have priority over mitigation or compensation measures, since soil sealing is an almost irreversible process (European Commission, 2012).

In general, the peri-urban fringes are the most actively changing areas and characterised by fast landscape dynamics, where urban densification and sprawl occur concurrently (Plieninger et al., 2016) and land-use conflicts are frequently observed (von der Dunk et al., 2011). Under these dynamics, the agricultural landscape is challenged and loses its priority status in short time (Tian et al., 2016; Tóth, 2012), despite its perceived multifunctionality and biodiversity values (Ives and Kendal, 2013; Zasada, 2011).

Among multifunctional land use values, the carbon (C) storage capacity plays a relevant role. Recent estimates state that globally, agricultural soils hold roughly 100 Pg of soil organic carbon (SOC) in their first 20 cm, and in Italy, this value adds up to 1.96 Pg SOC (Yigini et al., 2017; Yigini and Panagos, 2016). The SOC stocks under vegetated ecosystems show a large variability in and near urbanised areas, ranging from 20 to 230 Mg ha^{-1} (Curran-Cournane et al., 2015; Lorenz et al., 2003; Vasenev et al., 2013; Weissert et al., 2016).

Changes in land use and cover inevitably cause a change in soil C stock; thence, the question of how the process of "becoming urban" (Friedmann, 2016) - which characterises the peri-urban fringe evolution - can be approached in terms of C stocks and their distribution across spatial and temporal dimensions. Scalenghe et al. (2011) tackled such a question by quantifying the balance of natural and anthropogenic C stocks over a period of 150 years, concluding that soil sealing mainly results in losses of SOC stocks, which are substituted by C stored in concrete and other building materials, with an average net loss of around −0.5 Mg C ha^{-1} y^{-1}.

Studies on soil sealing evolution in peri-urban systems are restricted to single cities or small areas (*e.g.* Sui and Zeng, 2000; Long et al., 2007; Tian and Zhu, 2013). The scientific literature shows several examples of applications of remote sensing in urban and peri-urban studies (*e.g.* Herold et al., 2005; Huang et al., 2007; Vanderhaegen et al., 2015; Van de Voorde et al., 2016; Villa, 2012; Weng, 2012; Zhu et al., 2012). The possibility of mapping peri-urban C stocks based on remote sensing was explored by Villa et al. (2014), who investigated the use of medium resolution Landsat scenes for mapping SOC and C stocks in built-up structures, concluding that satellite data, at a scale of 500–1000 m, could effectively be used for this aim.

In this context, the main objectives of this work are: i) to map urban and peri-urban C stocks stored in soil and built-up surfaces and to assess their evolution across two decades (1993–2014) using satellite data; ii) to use C stock evolution information for quantitatively characterising urbanisation patterns and soil sealing dynamics at a detailed scale. For this, we focus our analysis on three hotspot areas: a thinly populated, an intermediate density and a densely anthropized area.

2. Materials and methods

2.1. Case studies

In the EU, the degree of urbanisation classifies local administrative units into three types (Dijkstra and Poelman, 2014): thinly populated area (mainly rural), intermediate density area (towns, suburbs or small urban areas) and densely anthropized area (cities or large agglomerated urban areas). We have selected these three typologies in the Emilia-Romagna region (North Italy), with a similar demographic structure and three different models of urban growth according to their degree of urbanisation (Fig. 1). All the three study areas (SAs) evolve in agricultural landscape, always >70% of the total area (reference year 2008; Regione Emilia Romagna, 2011b). According to their land capability (Malucelli et al., 2014), all of them develop on prime farmland (PF) soils, by definition the best arrangement of physical and chemical characteristics for producing food, feed, forage, fibre or energy crops (Soil Survey Staff, 1993).

2.1.1. Study area 1 - thinly populated area (Piacenza)

In this area, artificially modelled surfaces cover 14% (Regione Emilia Romagna, 2011b). The area around the city of Piacenza evolved from being almost completely agricultural with sparse rural settlements in the 1950s to the current situation, where commercial and logistic centres are the main drivers of soil sealing. A number of large storage warehouse settlements built in the hinterland of Piacenza during the last two decades (*i.e.* IKEA, Amazon) profoundly shaped the current landscape. According to the land use maps (Regione Emilia Romagna, 2011a, 2011b), productive settlements increased by >230% from 1976 to 2008 (2315 ha), while the residential urbanised areas increased by 11% (266 ha). The soils are mainly classified as PF soils (80.4%, see Table 1) and can sustain food consumption per average inhabitant of about 2.1 gha $person^{-1}$ (global hectares per person; Malucelli et al., 2014), with the global average being around 1.8 gha $person^{-1}$ (World Wild Foundation for Nature, WWF, 2012).

2.1.2. Study area 2 - intermediate density area (conurbation Reggio Emilia-Modena)

Here, artificially modelled zones cover about 22% of the total area. The landscape structure is shaped by the integrated forage and dairy farming system linked to the production of Parmigiano-Reggiano cheese, with sparse human settlements. The cropland parcellation is still that of the Roman *centuriatio*, dating back to the third century BC. Industrial activities started to develop in the 1920s around Modena, especially in agricultural machinery and automotive sectors, with brands such as Stanguellini, Bugatti, Maserati and Ferrari (Tozzi Fontana and Chirigu, 2014). This resulted in a diffuse urban sprawl and fragmentation of both transport infrastructures and residential areas, eventually taking the shape of an almost seamless conurbation connecting Reggio Emilia, Modena and the nearby municipalities. Productive settlements increased by 488% from 1976 to 2008 (6794 ha), while residential urbanised areas increased by 74% (5325 ha). The soils are predominantly PF soils (74.4%, Table 1) and sustain a food consumption per average inhabitant of <0.6 gha $person^{-1}$ (Malucelli et al., 2014), one third of the global average estimates.

2.1.3. Study area 3 - densely anthropized area (Rimini)

In this area, artificially modelled zones are close to 27%. Coastline areas, overbuilt in the second half of the last century, were subject to a rapid development of tourism, resulting in the construction of an almost uninterrupted series of hotels and apartment buildings, consisting of second homes or rental flats. Along the northern Mediterranean coast, this phenomenon can be observed in other areas and is referred to by several synonyms: 'Marbellisation' (in southern Spain), 'Azurisation' (at the French Riviera) or 'Riminisation', as in this case. From 1976 to 2008, productive settlement areas increased by 212% (2972 ha), while the residential areas increased by 62% (3423 ha) (Regione Emilia Romagna, 2011a, 2011b). Only half of the soils here are classified as PF soils (Table 1) and can sustain around 0.5 gha $person^{-1}$ (Malucelli et al., 2014), which is <30% of the global average.