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Towards a socioeconomic profile for areas vulnerable to soil compaction? A case study in a Mediterranean country

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ABSTRACT

The present study assesses the spatial distribution of 133 socioeconomic indicators compared with indexes of land vulnerability to natural/human-induced soil compaction in 8101 municipalities in Italy using an exploratory data analysis. The aim is to ascertain if local municipalities classified at high soil vulnerability are also characterized by a specific territorial profile. More than 30 indicators correlated with soil vulnerability to compaction reflecting the long-established interactions between rural communities and the landscape in turn shaped by latest socioeconomic changes. The present study has showed that factors discriminating vulnerable from non-vulnerable areas include demographic and socio-spatial processes (population concentration and aging), economic factors (specialization in tourism, industry and agriculture), environmental variables (i.e. soil erosion, salinization and sealing, forest fires and overgrazing) and landscape attributes (agricultural land-use diversity, crop intensity, land tenure). Land-use intensity, crop fragmentation, population density in rural areas and, more generally, human pressure variables are the factors mostly associated with high levels of (both natural and human-induced) soil vulnerability to compaction. Assessing latent relations between socioeconomic factors and soil vulnerability to compaction provides an in-depth understanding of the overall risk for soil compaction. Soil conservation strategies may benefit from improved knowledge of socio-ecological systems informing a more sustainable land management against soil degradation.

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1. Introduction

Soils play a key role in plant growing, agricultural production, water conservation, CO_2 sequestration, preservation of biodiversity and nutrient cycles (Acosta et al., 2013; Bellezoni et al., 2014; Ferrara et al., 2014; Huub and Holger, 2014; Wagg et al., 2014). As a non-renewable resource, soils undergo degradation limiting or inhibiting their functionality (e.g. Salvati et al., 2013a, 2013b). Soil compaction is a relevant degradation process at the global scale altering soil structure by mechanical pressure, mostly due to unsustainable agricultural practices (Nawaz et al., 2013; Soane and van Ouwerkerk, 1998). Compaction results in densification and distortion of the basic soil properties increasing the physical strength and reducing biological activity, permeability and porosity. Tracks, wheels, rollers, tillage practices and high livestock density can trigger compaction in cultivated soils (Soil Atlas of Europe, 2005).

Soil compaction reduces the space available to the roots limiting the absorption of water and nutrients from the plants and thus lowering crop yields (Drewry et al., 2008). Due to the pore-walls collapse, the altered soil structural stability leads to a reduced water infiltration capacity determining soil water saturation and the decrease of soil temperature (Bottinelli et al., 2014). These conditions reduce the activity of soil microorganisms and, thus, the decomposition of organic matter and release of nutrients (Beylich et al., 2010). Denitrification processes and production of toxic gases for plants close to the roots can also be observed in soils exposed to compaction (Batey, 2009). While having the effect to increase soil fertility in the short-term, conventional cultivation practices with mechanization and continuous use of chemical products, can determine a long-term decrease of soil organic matter with the consequent loss in soil quality (Duttmann et al., 2014). This leads to an increased use of technical means (machines, fertilizers, herbicides) with rising production costs and environmental pollution (Caicedo et al., 2014).

Compaction processes occur in most of the agricultural soils of developed countries. Compaction is the prevalent soil degradation process in Central and Eastern Europe with 25 million ha of land classified as moderately compacted and 36 million ha classified as severely affected by compaction (European Soil Portal, 1995-2014). Agricultural mechanization is the main driver of soil compaction in Europe (Soil Atlas of Europe, 2005) determining side effects related to the plastic deformation along both vertical and horizontal directions (Seehusen et al., 2014). The model proposed by Grecenko and Prikner (2014) based on the relationship between tire rating and compaction capacity, the

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vertical stress transmission model illustrated by Taghavifar and Mardani (2014) and, finally, the assessment framework introduced by Duttmann et al. (2014) definitely indicate crop intensification and changes towards less sustainable agricultural practices as key drivers of soil compaction. Forestry studies, also, demonstrate the negative effect of forest logging on physical and biological soil characteristics related to the slow recovery ability of natural topsoil (Ampoorter et al., 2012; Bottinelli et al., 2014; Goutal et al., 2012; Kleibl et al., 2014; Hartmann et al., 2014; Majnounian and Jourgholami, 2013).

Research identifies soil compaction as an important cause of land degradation in Europe and highlights the importance of the local socioeconomic context shaping soil vulnerability to compaction through different actions, including crop mechanization, overgrazing and increased livestock density, changes in the use of land, and other environmental degradation processes (Arbuckle and Lasley, 2013; Botta et al., 2012; Vorderbrugge and Brunotte, 2011). Environmental changes, agricultural policies and market conditions have been demonstrated to influence soil quality, vegetation cover and land-use patterns (Abu Hammad and Tumeizi, 2012; Basso et al., 2010; Lambin and Meyfroidt, 2010; Lopez-Vicente et al., 2014; Meusburger et al., 2012; van Zanten et al., 2014) triggering soil degradation (Montanarella, 2007). However, the inter-linkage existing between soil compaction, rural development and the socioeconomic profile of local communities has been poorly studied in Europe. As reported by Volk et al. (2010), this is clearly a limitation for soil conservation strategies since identifying relevant socioeconomic factors associated to soil compaction is vital for setting up effective mitigation actions.

Sustainable land management requires a permanent assessment of the level of soil compaction in conjunction with a thorough analysis of the relevant links between soil degradation and the socioeconomic context characterizing rural communities, especially in ecologically fragile areas (Basso et al., 2010). In this way, the influence of varying socioeconomic contexts on soil management can be deeply understood (Almansa et al., 2012). A number of models and approaches estimating soil compaction in Europe have been recently proposed (Al-Dousari et al., 2000; Caicedo et al., 2014; Défossez et al., 2003; Goutal et al., 2013; Horn and Fleige, 2003, 2005, 2009; Lagacherie et al., 2006). The European Soil Bureau (Joint Research Centre, Ispra) has prepared a continental map of natural soil susceptibility to compaction disseminating spatial data for the evaluation of compaction-driven soil degradation patterns (European Soil Portal, 1995-2014). Exploratory data analyses of the relationship between relevant biophysical and socioeconomic factors have contributed to more precise estimation of the degree of soil vulnerability to compaction (Tóth et al., 2013a, 2013b).

In the present study, we propose an exploratory data analysis of 133 indicators to identify the socioeconomic profile of 8101 Italian municipalities with different vulnerability of (natural and human-induced) soil compaction. Among the Mediterranean countries, Italy has a highly variable level of soil vulnerability to compaction (Perini et al., 2008). The present research contributes to shed light on issues such as the influence of socioeconomic factors on soil-landscape complex systems, with the aim of a better support to development policy against soil degradation. According to Salvati (2014), municipalities have been chosen as the elementary analysis' unit to describe the environmental conditions dealing with soil compaction and the related territorial context at the community level. Social, economic and environmental components' dynamics observed at the municipal scale may effectively illustrate the complexity of the long-established interactions between human activity and natural ecosystems in southern Europe (Conacher and Sala, 1998). The final objective of the study is to inform multidomain policies to protect soil in conjunction with other actions aimed at improving specific socioeconomic targets, which may influence positively the socio-environmental system affected by soil vulnerability to compaction. A thorough understanding of complex socio-environmental systems contributes to implement more effective, local-scale policies against land degradation embedded within country-scale strategies for soil conservation.

2. Methodology

2.1. Study area

Italy, a Mediterranean country extending for 301,330 km^2 and constituted by 23% flat areas, 42% hilly areas and 35% mountainous land, as reported in Salvati and Carlucci (2011), has been selected as the study area. Italy shows a pronounced north–south divide in climate, vegetation, soil, cropping systems and socioeconomic attributes such as per-capita income, population structure and labor market (Salvati and Carlucci, 2011). According to the 2001 administrative spatial partition of Italy, 8101 municipal councils (Fig. 1) and 20 regional authorities administer the country. The 2001 municipal configuration has been chosen since it allows using the largest number of socioeconomic variables available at the local scale from official statistics (Istat, 2006) that can be linked with a wide set of environment and soil data collected mainly in the late 1990s or the early 2000s (Perini et al., 2008).

2.2. Assessing soil compaction in Italy

Soil attributes, climate and land-use are contextual factors influencing the level of vulnerability to compaction, which directly depends on various soil physical and chemical properties (texture and depth, water regime, ground water level, soil biology). In this study, the estimation of soil vulnerability to compaction using homogeneous methodologies covering large areas is essential for both prevention and mitigation strategies and was preferred to the use of precise but local (e.g. point) and spatially-heterogeneous measures of soil compaction (Perini et al., 2008). Two approaches have been adopted here to illustrate the spatial pattern of soil vulnerability to compaction in Italy using (i) the map of natural susceptibility to soil compaction prepared by the European Soil Bureau of the Joint Research Centre (Ispra) and (ii) an assessment of soil compaction risk driven by agricultural mechanization using proxy indicators derived from official statistics. These approaches describe distinct dimensions of soil compaction based on natural and human-induced land vulnerability. The Joint Research Centre natural susceptibility map was developed from the attributes provided by the European Soil Database through the creation of relevant pedotransfer rules and refers to the year 2000. The map covers 27 member states of the European Union with 1 km^2 spatial resolution. Supplementary variables have been used according to knowledge experts on soil compaction (European Soil Portal, 2014).

Soil susceptibility to compaction was divided into four categories (1: low susceptibility to compaction, 2: medium susceptibility to compaction, 3: high susceptibility to compaction, 4: very high susceptibility to compaction). Areas where the estimation was neither relevant or it cannot be given due to lack of information were classified through a null code. ArcGIS software (ESRI Inc., Redwoods, USA) was used to calculate the natural soil susceptibility to compaction in each Italian municipality by overlapping the susceptibility map on the municipal boundaries' shapefile masking the surface areas classified as 'null'. A final index for each municipality (hereafter called Sus) was obtained as a weighted average of the four classes of soil susceptibility after attributing a susceptibility score to each of them (0.25: low, 0.5: medium, 0.75: high, 1.0: very high).

Human-induced vulnerability to compaction was evaluated as the result of unsustainable use of agricultural and forest soils. Agricultural mechanization estimated through elaboration on the number and power of the tractors available per farm, is considered the most relevant vulnerability factor for land exposed to soil compaction in Italy (Perini et al., 2008). Based on an indicator originally proposed by the Italian National Agency for the Protection of the Environment and validated by Perini et al. (2008), a vulnerability index for human-induced soil

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