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Spatial variability of soil aggregate stability at the scale of an agricultural region in Tunisia

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ABSTRACT

Soil aggregate stability is a key factor in soil resistance to water erosion, which is a threat to soils in a large part of northern Tunisia. The analysis of the spatial variability of soil aggregate stability provides both agronomic and environmentally useful information. However, extensive measurements of soil aggregate stability remain tedious and expensive.

This study explores two different approaches as alternative to measurements of soil aggregate stability. One approach estimated aggregate stability via laboratory measurements of soil elementary properties using multiple linear regressions known as pedotransfer functions. The second approach, which is methodologically innovating, was based on the geological pattern as a proxy for aggregate stability using regression-kriging analysis. A set of 113 soil samples from an 800 km^2 agricultural region that included the Lebna watershed (Cap Bon, Tunisia) were collected from the soil surface layer (0–10 cm depth). Samples were analyzed for elementary properties (i.e., soil texture, total carbon and nitrogen, iron, $CaCO_3$, salinity, CEC and pH) and for soil aggregate stability according to the normalized method (ISO/DIS 10930, 2012), which considers three indexes (MWD) calculated for three contrasted wetting conditions and disruptive energies.

Most soils in the study area were non-salted with an alkaline pH and relatively low organic carbon content. Of the soils, 35% were clay soils, and 55% had a balanced soil texture. The average of the three soil aggregate stability indexes (MWD_{mean}) ranged from 0.38 to 2.80 mm, and this property showed large variability from instable soils to very stable ones. Analysis of pedotransfer functions determined that the best predictor variables for soil aggregate stability were silt, organic matter and iron. Geostatistical analyses at the regional scale showed spatially structured soil aggregate stability (variograms with sills reaching a 5 km distance). Using geological information as ancillary data, the prediction of soil aggregate stability with regression-kriging was similar to that of pedotransfer functions. A regression-kriged map of soil aggregate stability associated with a map of prediction uncertainties was developed. The resulting maps and methods of this study can be useful in the development of management options that minimize water erosion risks in the studied area.

1. Introduction

Soil is a key component of the biosphere that determines the biogeochemical, hydrological and erosional cycles and delivers various essential ecosystems goods and services (Brevik et al., 2015; Keesstra et al., 2016). However, soils are often threat by several degradation factors among them soil erosion which is a clear indication of land degradation in the Mediterranean (García-Ruiz et al., 2013; García-Ruiz et al., 2017; Montanarella et al., 2016). Therefore preventing and combating soil erosion is a major environmental and economical challenge in this region where climate change is already perceptible (Den Biggelaar et al., 2004; Giorgi and Lionelle, 2008; Raclot et al., 2016). In Tunisia, the problem of soil erosion is more pronounced in the north part of the country in which the landscape is hilly and high-energy storms are frequent on bare soils during the autumn season (Jebari, 2009). Indeed, Kefi et al. (2012) show that 25% of the Tunisian septentrional area had an estimated annual soil loss rate that exceeded 30 t ha^{-1}.

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Aggregate stability is an intrinsic property of soils that is an empirical measurement (Le Bissonnais, 1996) of the ability of a soil aggregate to retain cohesion and not disintegrate under the action of water (Lal, 1991). Aggregate stability is particularly important to consider when issues are examined that relate to soil fertility and natural resources conservation (Cammeraat and Imeson, 1998; Amezketa, 1999; Bronick and Lal, 2005). Indeed, soil aggregate stability is used to evaluate the sensitivity of soil to crusting and erosion (Le Bissonnais, 1996; Cerdà, 2000; Barthès and Roose, 2002), the conditions for seed germination and rooting of crops (Lynch and Bragg, 1985) and the soil capacity to sequester organic carbon (Fenton et al., 2005). Therefore, the capacity to provide spatial predictions of this property is fundamental for landscape managers.

Research on soil aggregate stability is an essential requirement considering the importance of water erosion damages on site and off site (Keesstra et al., 2016; Montanarella et al., 2016). Indeed, soil aggregate stability is a definitive variable to understand soil erosion processes in agricultural and forest soils (Cerdà, 2000; García-Orenes et al., 2012; Haregeweyn et al., 2013) since soil aggregate stability seemed to reflect better the actual vulnerability of topsoils to physical degradation (Stanchi et al., 2015). Moreover, soil aggregate stability studies serve as early warning signs of vulnerability and resilience of soils and can be very useful for evaluating the impacts of land use and erosion control management (Cammeraat and Imeson, 1998; Cerdà, 2000).

Soil aggregate stability is studied by examining the process of aggregate disintegration or the factors that stabilize aggregates. The primary mechanisms of aggregate breakdown are slaking, breakdown by differential swelling, mechanical breakdown by raindrop impact and physicochemical dispersion (Le Bissonnais, 1996). The relative importance of these mechanisms depends on the patterns of rain and the physical and chemical properties of soils. Stabilizing factors are primarily related to soil characteristics, which may be affected by agricultural practices. Aggregate stability generally increases with the content of clay and organic matter in soil, but a significant universal equation adapted to all types of soils and conditions has not been established (Le Bissonnais and Arrouays, 1997; Le Bissonnais et al., 2007; Chenu et al., 2011; Mamedov et al., 2016). Other parameters such as soil microorganisms and their activities and cations (Ca^{2+} and Fe^{2+}, among others) are also involved in soil aggregation and stabilization (Lynch and Bragg, 1985; Wuddivira and Camps-Roach, 2007).

The spatial distribution of soil structure and stability is a key element in water and soil functions, and therefore, the determination is relevant to understand and manage soil processes to sustain agro-ecosystems (Shukla et al., 2007; Van Es et al., 1999). Spatial variability is inherent due to geologic and pedologic soil forming factors, but a part of this variability may be induced by tillage and other management practices. However, information on the spatial variation of aggregate stability in a given region remains limited (Mohammadi and Motaghian, 2011) compared with that for other soil properties such as soil water retention parameters (Heiskanen and Makitalo, 2002; Iqbal et al., 2005), texture (Jung et al., 2006; Ließ et al., 2012) and organic carbon content (Stutter et al., 2009; Hoffmann et al., 2014; Hu et al., 2014).

The first objective of this work was to determine the degree of spatial organization of levels of soil aggregate stability at the scale of an 800 km^2 agricultural region. The second objective was to assess two different approaches to predict soil aggregate stability: i) one approach used pedotransfer functions consisting of multiple linear regressions based on conventional soil properties, and ii) the other approach was regression-kriging based on ancillary spatial data, which in this study, were the geological substrate data. The second approach tested here is, to our knowledge, applied for the first time to soil aggregate stability studies. Assessment of the two approaches was performed using a leave-one-out cross-validation (LOOCV) technique applied to a sample collection of 113 soil samples from an agricultural region located on the Cap Bon Peninsula in the northeast of Tunisia.

2. Materials and methods

2.1. Site description and sampling

Soil samples were collected in a hilly, rural area covering approximately 40 × 20 km between the southeastern flank of the Djebel Abderrahmane anticline and the east coast of the Cap Bon Peninsula in northeast Tunisia (36°24″–53″ N, 10°20″–58″ E; Fig. 1a). The elevation of the study area ranges from 250 m at the foot slope of the Djebel (west of the study area) to 20 m near the coast (east of the study area). The area includes most of the Lebna watershed, which drains into the Lebna reservoir. The climate is at the boundary between Mediterranean sub-humid inferior and Mediterranean semi-arid superior with an average annual rainfall ranging from 650 mm in the west to 450 mm in the east of the study area, a mean annual temperature of approximately 18 °C and an interannual potential evapotranspiration of approximately 1200 mm.

The primary soil types are regosols and eutric regosols predominantly associated with sandstone outcrops, calcisols associated with sandy

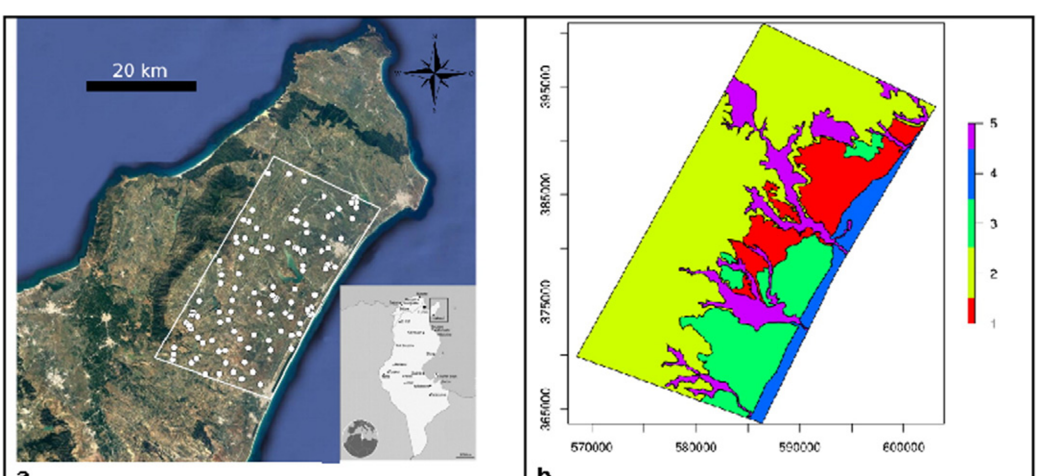

Fig. 1. a) Location of the study area in the Cap Bon region in northeastern Tunisia and those of the 113 soil samples (white dots). b) Geological information derived from the Tunisian geologic map 1/50000 (Bensalem, 1989) categorized into 5 geological units (1: alternation of soft-sandy layers and the thin layers of hard calcareous sandstone with Pliocene marine origin; 2: marls intercalated with Serravalian-Tortonian sandstone beds; 3: geological unit 1 encrusted with limestone; 4: recent coastal deposits; 5: recent and old terrestrial deposits near the wadis). X- and Y-axes are Lambert Tunisian coordinates in meters.