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Soil aggregate stability within morphologically diverse areas

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ABSTRACT

Knowledge of spatial distribution of soil aggregate stability as an indicator of soil degradation vulnerability and its possible prediction are required for many scientific and practical environmental studies. The goal of our study was to provide a model for predicting soil aggregate stability within morphologically diverse areas, where soil properties have been affected by soil material redistribution due to erosion. The study was performed on a study site (6 ha area) in the loess region of Southern Moravia, Czech Republic. Haplic Chernozem, which is an original dominant soil unit, has been transformed into different soil units (eroded phases of Chernozem, Regosol, colluvial Chernozem and Colluvial soil). 36 sampling spots were selected in order to represent diverse soils. The following soil properties were measured: oxidable organic carbon content (C_{ox}), $CaCO_3$ content, pH_{H_2O}, pH_{KCl}, soil particle density (ρ_s), bulk density (ρ_d), porosity (P), actual field soil-water content (θ_{field}), content of iron and manganese (in ammonium oxalate extract, Fe_o and Mn_o, and dithionite–citrate extract, Fe_d and Mn_d) and mass specific magnetic susceptibility (χ_{lf} and χ_{hf}). The aggregate stability was assessed using various tests to study different disruption mechanisms. Terrain attributes were derived from a digital elevation model.

In general, the lowest soil aggregate stability was observed on steep slopes, which were highly impacted by soil erosion. The highest aggregate stability was measured on soils sampled at relatively flat upper parts, which were less influenced by erosion processes. Higher stability was also obtained on toe slopes, where the sedimentation of previously eroded soil material occurred. The simple correlations revealed that characteristics resulting from the tests studying aggregate slaking due to the compression of the entrapped air (Water Stable Aggregate index and coefficient of vulnerability from fast wetting test) were positively impacted by the C_{ox}, P, Fe_o, Mn_o, Fe_d, Mn_d, χ_{lf} and χ_{hf} values, and negatively by the ρ_d value. The soil aggregate stability was also negatively influenced by the plan and total terrain curvatures, i.e. larger aggregate stability was measured at concave parts in comparison with that at convex parts. Almost no statistically significant relationships were found in the case of the tests evaluating either aggregate disintegration caused by the micro-cracking due to the different swelling, or by the physico-chemical dispersion due to the osmotic stress or the mechanical aggregate breakdown. The multiple linear regressions resulted in the model for estimating the WSA index using the C_{ox} content, total terrain curvature and actual field soil-water content (θ_{field}). In this model the C_{ox} content positively and the total terrain curvature and θ_{field} value negatively influenced the value of the WSA index. Since C_{ox} was positively related with iron content and thus also with the magnetic susceptibility, the alternative model was proposed for less costly and time consuming WSA estimation. The WSA index may be predicted by combining the mass specific magnetic susceptibility (χ_{lf} and χ_{hf}), total terrain curvature and actual field soil-water content (θ_{field}).

1. Introduction

Knowledge of soil aggregate stability, which is one of the characteristics of soil structure, is essential when assessing soil vulnerability to degradation. An enhanced aggregate stability decreases the losses of soil, carbon, nitrogen, and phosphorus (Kasper et al., 2009), and increases the amount of macro-aggregates and the total and effective porosity (Shaver et al., 2002). The soil aggregate stability influences water flow and contaminant transport in soils (Kodešová et al., 2009b). Soil aggregation is under the control of different mechanisms in different soil types. Generally, the level of aggregation and the stability of aggregates increase with increasing organic matter content, surface area of clay minerals, and cation exchange capacity (Bronick and Lal, 2005). Flocculated clay particles, or their complexes with humus (organo-mineral complexes) and soil organic matter, act as the main cementing agents in soil aggregates. Aggregate stability depends on the nature of the organic inputs (Abiven et al., 2009). Easily decomposable products have a transient impact on aggregate stability while more recalcitrant products have a longer term effect. The cementing effect of free Fe and Al oxides is important in soils with low organic matter content (Barral et al., 1998; Six et al., 2002). The state of colloidal systems is

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strongly influenced by cations and soil sesquioxides (Valla et al., 2000). When microaggregates are formed by binding of multivalent cations (Ca^{2+}, Fe^{2+}, Al^{3+}) and humus, they exhibit high stability. Conversely, if they are bound by the Na^{+} cations, or if there is a dispersion of clay particles, the soil becomes without structure and impermeable for water and air. The positive impact of calcium on aggregate stability was revealed in soils with low activity minerals (Wuddivira and Camps-Roach, 2007). The low soil pH may also increase the aggregate stability due to the behavior of acidoids prevailing in soils, which peptize at abundance of OH^{-} (Valla et al., 2000). Clay and organic matter coatings covering soil aggregates in some horizons of particular soil types may protect aggregates against destruction (Kodešová et al., 2009a). Hydrophobicity may increase aggregate stability due to slow wetting (Goebel et al., 2005; Vogelmann et al., 2013). Agricultural management considerably affects many soil properties including soil structure and its stability. By tillage, the topsoil is mixed and aggregates are exposed to different breakdown mechanisms (Six et al., 1998, 2000). As a result, soil structure and associated soil properties of tilled soil vary in time due to the variable impact of destruction forces and aggregate forming processes (Jirků et al., 2013; Strudley et al., 2008). Soil tillage at improper soil moisture, crossing of heavy machinery, irrigation, and use of fertilizers can also lead to serious soil structure degradation (Pagliai et al., 2004).

Soil structure and soil aggregate stability are closely related to the surface runoff and soil erosion processes. Aggregate stability may be used as an indicator of soil susceptibility to runoff and erosion (Barthe and Roose, 2002; Cantón et al., 2009; Le Bissonnais et al., 2002). Erosion/deposition processes modify soil properties, i.e. also soil aggregate stability (Stavi and Lal, 2011; Zádorová et al., 2011a). Soil redistribution within the morphologically diverse area may be related to terrain attributes and therefore soil property distributions could be predicted using digital terrain modeling (i.e. Borůvka and Penížek, 2006; Florinsky et al., 2002; McBratney et al., 2003; Moore et al., 1993; Odeh et al., 1995; Sumfleth and Duttmann, 2008). Soil properties that are most frequently related to selected terrain attributes are the soil depth, particle size distribution, organic carbon content, soil moisture and selected nutrients. Only a few studies were performed on the soil aggregate stability spatial distribution and its relationship with topography. The studies were mostly focused on the evaluation of soil aggregate stability at selected topographic positions like study by Le Bissonnais et al. (2002), who studied aggregate stability at five positions along vertical transects delineated at three fields with different soil types. Direct relationship with topographic attributes was studied by Cantón et al. (2009) and Zádorová et al. (2011a).

The soil aggregate stability could be assessed using various methods, which also relate to different aggregate breakdown mechanisms (Amézketa, 1999). The index of water stable aggregates (WSA index) (Nimmo and Perkins, 2002) is one of the most frequently evaluated parameters. A complex approach presented by Le Bissonnais (1996), proposed three tests to study various destruction mechanisms: 1) The fast wetting test for studying aggregate slaking due to the compression of the entrapped air (mechanism similar to the WSA test), 2) the slow wetting test for evaluating aggregate disintegration caused by the micro-cracking due to the different swelling, and physico-chemical dispersion due to the osmotic stress, 3) the shaking after prewetting test for assessing the mechanical aggregate breakdown. The aggregate disintegration due to raindrop impact (Loch and Foley, 1994) or ultrasonic aggregate dispersion (Edwards and Bremner, 1967) combined with novel laser granulometry (Rawlins et al., 2013) may also be studied. Finally, the dry sieving (Kemper and Chepil, 1965) was also used in numerous studies.

While Le Bissonnais et al. (2002) used the complex method of 3 tests to evaluate aggregate stability under different conditions in different segments of the slope system, Cantón et al. (2009) applied dry sieving and the raindrop test and Zádorová et al. (2011a) used the WSA index test to evaluate aggregate stability with respect to terrain attributes. In all cases soil aggregate stability was mostly influenced by the soil organic matter content. Le Bissonnais et al. (2002) also proved the correlation with the clay content. Significant relationship between the aggregate stability and clay content was not found in the other two cases due to low clay content (Cantón et al., 2009) and low spatial variability of clay content (Zádorová et al., 2011a). Results of the fast wetting test in Le Bissonnais et al. (2002) showed higher aggregate stability at downslope sites than upslope sites. Cantón et al. (2009) found a relationship between the wet aggregate stability and profile curvature, indicating that more stable aggregates were found on convex areas. However, their study did not prove that terrain attributes played a significant role in overall aggregate stability and in spatial distribution of soil organic matter and soil texture. Zádorová et al. (2011a) presented a relationship between the WSA index and plan curvature. They showed that the lower aggregate stability was found at convex areas.

Precise description and possible prediction of spatial distribution of soil aggregate stability as an indicator of soil vulnerability to erosion within areas strongly impacted by soil material redistribution are needed for a wide range of environmental studies (catchment hydrology, yield prediction, contaminant transport etc.). Previous studies documented the influence of particular factors or some combinations of selected factor on some of parameters characterizing the soil aggregate stability due to different destruction mechanisms. None of them provided complex study including all relevant soil chemical and physical

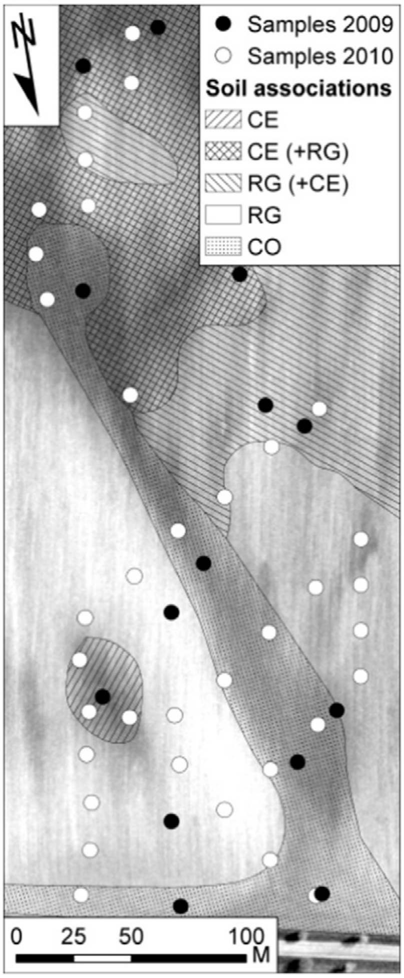

Fig. 1. Soil associations with spatial location of soil samples taken in November 2009 (black dots) and in August 2010 (white dots): CE — Chernozem, RG — Regosol, CO — colluvial Chernozem and colluvial soil.