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Ongoing oversanding induces biological soil crust layering – A new approach for biological soil crust structure elucidation determined from high resolution penetration resistance data

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ABSTRACT

The aim of this study was to determine the in-situ strength and microscopic characteristics of bio-physical micro-horizons in the top 40 mm of oversanded sand soils detected by depth dependent penetration resistance (PR). These micro-horizons result from the burial of biological soils crust (BSC) surfaces and contribute to soil stability. They are also important as the biotic source for seeding new surficial crusts. Ex-situ polarised optical micrograph was employed to determine the bio-physical structures associated with the fossil BSC horizons. An automated electronic micro penetrometer (EMP) determining in-situ depth dependent soil PR was used for the quantitative detection of surface and buried micro-horizons. PR data was modelled using a multi-component/soil and micro-horizon multilayer plastic shear stress model. This enabled determination of soil and sediment structure, the contribution of buried 'fossil' BSCs to soil strength and structural mapping. We also employed proxy (synthetic) layered soil systems to determine the effect of EMP shaft and probe tip shape upon the PR profile. This methodology represents a significant improvement over penetrometer methods that only use single-value surface breaking point information. We find that buried BSC structures can contribute over 80% of the soil strength even at ca. 20 mm depth and that the strength of a buried crust, at least in the medium term, can exceed that of (developing) surficial ones. Typical soil strengths of BSCs in the Negev desert, Israel lie between 1.5 and 3.6 MPa. Finally we discuss the effects and potential importance that buried BSC horizons may have upon heat, and the percolation and diffusion of moisture and gas through structured bio-physical, BSC capped sand soil systems.

1. Introduction

Biological soil crusts (BSCs) cover large areas of dryland soils in arid and semiarid areas (Belnap et al., 2016) and are considered a key element in landscape stability (Jimenez Aguilar et al., 2009). BSC organisms are able to grow under high light intensities and have developed various survival strategies in order to cope with harsh environmental conditions, such as frequent hydration and desiccation (Fierer et al., 2003; Pócs, 2009; West, 1990). As drylands cover approximately 40% of the global land surface and support 38% of the human population (Reynolds et al., 2007), BSC covered soils are of significance to soil-atmosphere coupling and hence, potentially, an important part of global climate change models (Elbert et al., 2012; Thomas and Hoon, 2010). Although often no more than a few millimetres in thickness, BSCs inhibit wind erosion and are important in protection against land degradation (Belnap and Gillette, 1998; Rodríguez-Caballero et al., 2013; Zhang et al., 2006). A recent study by Lan et al. (2014) proves that the artificial introduction of BSCs can even facilitate the reversal of desertification. Apart from lichens and, in part, bryophytes, cyanobacterial strains are the principal biomass producers in many desert soils (Belnap et al., 2003). Cyanobacteria during their growth excrete extracellular polymeric substances (EPSs), forming a polymeric matrix (Chen et al., 2014), which in early stage crusts constitutes the main source for organic carbon in the soil (Mager, 2010). EPSs stabilise the soil surface (Hu et al., 2003a) and foster pedogenic processes in young soils (Dümig et al., 2014). Further, EPSs swell during hydration (Fischer et al., 2010) and are able to capture deposited dust (Williams et al., 2012). This dust accumulation and the input of salts also contributes

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significantly to BSC aggregation and stabilisation (Drahorad and Felix-Henningsen, 2013; Zaady and Offer, 2010). Recent studies show that the overall stability of BSCs is strongly linked to their development and environmental conditions, such as land use history and soil properties (Chamizo et al., 2015). A complex symbiotic community exists within BSCs. Lichens, bryophytes, mycorrhiza, bacteria, algae, cyanobacteria and fungi, the binding of soil particles by EPS sheaths and a stratified grain structure all contribute to the strength of BSCs. This biological community results in a cohesive crust possessing structural and consequently deformational properties that are expected to differ from the matrix of the underlying host soil. The mechanical stability of BSCs strengthens as their age, thickness and biomass increase. For the Negev desert, Israel, Kidron et al. (2010) observed an increase in strength with ongoing succession from 0.009 to 0.076 MPa. Guo et al. (2008) found an increase in penetration resistance from 0.108 MPa for physical crusts to 0.126 MPa and 0.165 MPa for algal and moss crusts, respectively, on a stabilised sand dune surface in Inner Mongolia, China. Thomas and Dougill (2007) found the penetration resistance (PR) to increase with crust succession from 0.055 to 0.147 MPa in the Kalahari Desert, Botswana. For BSCs in the Karoo desert, South Africa, Dojani et al. (2011) found the mean penetration resistance to be 0.206 MPa. For a semi-arid steppe in SE Spain, Maestre et al. (2002) report the maximum penetration resistance of BSCs to be 0.698 MPa. Chamizo et al. (2015) have measured the PR of different crust types at two study sites in SE Spain in wet and dry states, as well as before and after crust removal. They found that the PR varied from 0.149 to 0.310 MPa and that both soil moisture content, and disturbance had a major effect on crust stability. Although these values vary significantly (due to in part to differences in methodology), this wide range of PR values is proof for the high site and soil substrate dependency of crust stability. However, what all these measurements have in common is that they only provide information on the maximum surface PR. BSCs also possess a vertical stratigraphy with regard to their stability and composition that is dependent upon metabolic differences in the organisms involved (Drahorad and Felix-Henningsen, 2013; Hu et al., 2003b; Kidron et al., 1999). Several studies from different arid and semiarid regions describe the existence of a thin, biologically enriched topcrust and a partly indurated section below this crust, referred to here after as a subcrust (e.g. Lan et al., 2012; Malam Issa et al., 2009) extending to a depth no > 50 mm below the surface. Williams et al. (2012) found two macro scale layers for BSCs of the Mojave Desert, USA, often separated by a lateral linear void. In addition to being caused by a higher degree of aggregation in the upper layer, this void is also related to a change in the pore system, i.e. the occurrence of vesicular pore structures. These vesicles can occur either within the subcrust or underneath the BSC as a fully developed vesicular horizon (designated Av). These pore systems have been found in both desert BSCs (Felde et al., 2014) and temperate region physical soil crusts (Badorreck et al., 2013). Some studies indicate that the subcrust and the underlying soil can contain old, oversanded crusts (Drahorad and Felix-Henningsen, 2013; Felde et al., 2014; Malam Issa et al., 2009) resulting in crust layering. This crust layering can be the result of either horizontal or vertical recolonization after burial. Studies from China have shown, however, that if oversanding exceeds a critical threshold of 1 cm, it causes severe damage to crust organisms inhibiting their functionality (Rao et al., 2012) and, importantly, these buried crusts are not able to regenerate but remain more or less as a stable relict. Consequently, the new surface has to be colonized horizontally by pioneer crust organisms from neighbouring unburied crusts. If a recolonization does not take place, these buried BSCs are prone to erosion, once they are re-exposed (Kidron et al., 2016). Less intense oversanding, however, may allow mobile BSC organisms such as *Microcoleus vaginatus* to move upwards (Garcia-Pichel and Pringault, 2001) and recolonize the new surface vertically, rather than horizontally (Belnap et al., 2003), forming a new topcrust. Thus, in sandy semiarid and arid soils buried BSCs are of great importance for topsoil stability, nutrient storage and turnover (Drahorad et al., 2013) as well as water storage and water redistribution (Felde et al., 2014). The use of penetration resistance (PR) data from field penetrometers for soil and sediment structure analysis and structural mapping has been reported in other studies (e.g. Anderson et al., 1980; Boon et al., 2005; Grunwald et al., 2001; van Herwijnen et al., 2009; Olsen, 1990). The BSCs of the Negev desert have been studied for over three decades, resulting in a comparatively good understanding of many of their ecological roles. For example, numerous studies have shown their importance for the carbon and nitrogen cycle (Drahorad et al., 2013; Kidron et al., 2015a, 2015b; Russow et al., 2005; Wilske et al., 2008), as well as different hydrological processes, such as surface runoff, evaporation and hydrophobicity (Keck et al., 2016; Kidron and Tal, 2012; Yair et al., 2011) or their effect on annual and perennial plants (Almog and Yair, 2007; Kidron, 2014; Prasse and Bornkamm, 2000).

However, the effect of sand burial and the resulting buried crust structures on BSC properties is largely unknown. Hence, the aim of this study was to determine the strength of micro-horizons resulting from the burial of old BSC surfaces using an automated electronic micro penetrometer (EMP, for a detailed description see Drahorad and Felix-Henningsen, 2012) in order to better understand their role in overall crust stability. The particular advantage of the automated EMP employed here is its ability to ensure constancy or equivalence of operation, in particular its uniform penetration rate (16 mm min^{-1} or 267 μm sec^{-1}) enabling variation in the driving force to be related to intrinsic soil yield stresses. This study is the first to combine high resolution PR data and modelling for detailed structural elucidation of BSCs at high resolution. In order, however, to be able to properly interpret variations in PR in terms of corresponding soil micro structure, a model relating PR to layering is required. Here we present a mathematical model developed to interpret and characterise PR profiles, small scale boundaries and compositional changes within BSC covered topsoils based on the premise that the strength of soils, specifically their plastic yield and depth dependent deformation stress, can be determined using a soil penetrometer. We present data determined by the EMP interpreted using this model. The occurrence and stability of buried BSCs and layers on sub millimetre length scales has been detected. Our measurements and field observations of PR show the importance of morphological layering to overall BSC function as discussed below.

2. Material and methods

2.1. Study site and BSC sampling

All field measurements and the BSC sampling were made in March 2013 at the beginning of the dry season at the study area *Nizzana-south*, in the NW Negev, Israel within the field site of the Arid Ecosystem Research Center of the Hebrew University of Jerusalem (Fig. 1).

The area is characterised by linear sand dunes, which are covered by BSCs on the dune flanks and in the interdunal valleys but possess uncrusted mobile dune crests due to high wind speeds preventing crust establishment (Kidron and Yair, 2008). The BSCs continue to undergo successional recovery as a consequence of land use exclusion since re-establishment of the Egyptian-Israeli Sinai border in 1982 (Tsoar, 2008). The average annual rainfall is ca. 90 mm with high inter annual variations (Littmann and Berkowicz, 2008). The BSCs are dominated by cyanobacteria, such as *Trichocoleus sociatus*, *Microcoleus vaginatus*, *Scytonema* sp. and *Nostoc ssp.* (Büdel and Veste, 2008). For the characterisation of BSC properties, 3 samples were taken randomly on south facing dune slopes within an area of approximately 3 square metres. Sampling of the soil was made at three depths; the active biological topcrust (0–2 mm), a more or less cemented subcrust at up to ca. 20 mm, and the topsoil to an absolute depth of 10 cm. In addition, the unconsolidated loose surface sand of the dune crest was sampled to serve as a proxy for uncrusted soil. All soil samples removed for ex-situ analysis in the laboratory were subsequently oven-dried (40 °C), sieved