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Assessment of physical and hydrological properties of biological soil crusts using X-ray microtomography and modeling

M. Menon [a,*], Q. Yuan [b], X. Jia [b], A.J. Dougill [a], S.R. Hoon [c], A.D. Thomas [c], R.A. Williams [b]

[a] School of Earth and Environment, University of Leeds, LS2 9JT, UK
[b] School of Process, Environmental and Materials Engineering, University of Leeds, LS2 9JT, UK
[c] Department of Environmental & Geographical Sciences, Manchester Metropolitan University, M1 5GD, UK

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SUMMARY

Biological soil crusts (BSCs) are formed by aggregates of soil particles and communities of microbial organisms and are common in all drylands. The role of BSCs on infiltration remains uncertain due to the lack of data on their role in affecting soil physical properties such as porosity and structure. Quantitative assessment of these properties is primarily hindered by the fragile nature of the crusts. Here we show how the use of a combination of non-destructive imaging X-ray microtomography (XMT) and Lattice Boltzmann method (LBM) enables quantification of key soil physical parameters and the modeling of water flow through BSCs samples from Kalahari Sands, Botswana. We quantify porosity and flow changes as a result of mechanical disturbance of such a fragile cyanobacteria-dominated crust. Results show significant variations in porosity between different types of crusts and how they affect the flow and that disturbance of a cyanobacteria-dominated crust results in the breakdown of larger pore spaces and reduces flow rates through the surface layer. We conclude that the XMT–LBM approach is well suited for study of fragile surface crust samples where physical and hydraulic properties cannot be easily quantified using conventional methods.

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1. Introduction

Biological soil crusts (BSCs) are formed by an intimate association between soil particles and cyanobacteria, green algae, microfungi, bacteria, lichens and bryophytes which live within or immediately on top of the uppermost millimeters of soil (Belnap and Gardner, 1993). Due to their low moisture requirement and tolerance to extreme temperature and light, they dominate the ground cover in many dryland systems which cover more than one-third of the global land area (Belnap, 2003). For example, in undisturbed areas of Kalahari Sand soils in Botswana, BSCs cover reaches 95% of the soil surface (Dougill and Thomas, 2004). Multiple classification systems are available based on appearance, biomass, and species composition of BSCs (Belnap, 2003). For instance, Thomas and Dougill (2007) used surface characteristics to classify BSCs from Kalahari Sands and linked this to their strength, erosivity and organic carbon content (Berkeley et al., 2005).

BSCs play vital hydrological, geomorphological and ecological roles in drylands (Evans and Johansen, 1999; Viles, 2008). Several studies have demonstrated their roles on controlling soil carbon cycling process including regulation of both photosynthesis activity and soil respiration (Housman et al., 2006; Lange et al., 1998; Thomas and Hoon, 2010), nitrogen fixation (Belnap, 2002; Büdel et al., 2009; Wu et al., 2009), soil aggregation (Belnap, 2006; Zhang et al., 2006), and soil erosion prevention (Belnap, 2006; Eldridge et al., 2000; Ram and Aaron, 2007).

However, the influence of BSCs on hydrological processes such as infiltration remains uncertain and controversial (Belnap, 2006; Evans and Johansen, 1999) due to the lack of measurements of key physical measurements which determine the flow through the surface crust. Warren (2003) analyzed previous studies on infiltration and found that out of 24 field-based studies on infiltration, seven showed that the presence of biological crusts increased infiltration, six showed no effect, and 11 showed decreased infiltration. Warren (2003) concluded that the presence of crusts decreased infiltration as sand content increased (>66%) and increased infiltration as clay contents increased (>15%). However, it is well established that other soil physical properties such as soil structure, porosity and pore characteristics (size, shape, connectivity, tortuosity) significantly influence water flow through soil and these have not been measured in crust hydrology studies to date.

* Corresponding author. Tel.: +44 113 343 1635; fax: +44 113 343 5259.
E-mail addresses: m.menon@leeds.ac.uk (M. Menon), q.yuan@leeds.ac.uk (Q. Yuan), x.jia@leeds.ac.uk (X. Jia), a.j.dougill@leeds.ac.uk (A.J. Dougill), S.Hoon@mmu.ac.uk (S.R. Hoon), A.D.Thomas@mmu.ac.uk (A.D. Thomas), r.a.williams@leeds.ac.uk (R.A. Williams).

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Data on these underlying soil physical parameters would form a stronger physical basis and help interpret the infiltration data and ascertain the role of BSCs on crusts on infiltration (Belnap, 2006). However, measurement of structure or porosity without disturbance to the crusts is a methodological challenge, especially when dealing with fragile samples like BSCs.

In addition to porosity and pore characteristics, infiltration or run off are also affected by several other properties of the BSCs such as pore clogging or hydrophobicity, depending on the type and the amount of organisms in the crust (Belnap 2006). Most organisms have the ability to swell upon wetting contributing to hydrophobicity and the clogging of soil pores (Verrecchia et al., 1995; Kidron et al., 1999). Similarly, when BSCs are disturbed mechanically, infiltration can be significantly affected (Eldridge et al., 2000) due to the changes in structure, porosity and pore characteristics. The effect depends fundamentally on the type of crust, the amount of force applied and initial moisture conditions. The effect of mechanical disturbance on infiltration can be only explained with the help of porosity or bulk density changes before and after the application of force and as yet no studies quantify the impact of mechanical disturbance on structure and porosity of fragile dryland soil crusts.

In order to establish the influence of BSCs on infiltration, we need to develop and apply non-destructive quantification of porosity and structure and an independent assessment of flow which is based on key soil physical properties and not affected by field disturbance or properties of crusts such as hydrophobicity or pore clogging. Given this, we formulated the following objectives for this study:

(1) to quantify and assess porosity and structure of different types of BSC from a study site in the Kalahari using non-destructive X-ray microtomography (XMT) and the modeling of flow using Lattice Boltzmann method (LBM) and
(2) to assess the impact of mechanical disturbance (vertical impact) on the porosity of, and flow through, a cyanobacteria-dominated BSC.

2. Methods

2.1. Sample collection and preparation

BSC samples were collected from a southern Kalahari location near Tsabong (26°3'S–22°27'E), Botswana where a series of ongoing studies are assessing the biological and biogeochemical make up of crusts (Berkeley et al., 2005; Thomas and Dougill, 2007; Mager, 2010; Thomas and Hoon, 2010). Kalahari sand soils are typically 96–98% fine sand and are found across an area of over 2 million km^2 of southern Africa (Wang et al., 2007). The mean annual rainfall of the study site is *c.* 320 mm. The BSCs of Kalahari are classified into three types based on their form and morphology (Dougill and Thomas, 2004), as represented in Fig. 1. Type 1 BSCs represent the early stage of crust formation indicated by a delicate and thin layer of aggregated sand materials on the surface, often buried under aeolian deposits with no distinct colouration. Type 2 crusts are a few millimeters thick with speckles of colouration, whereas Type 3 crusts are dark brown or black in colour with a clear surface microtopography. Both Types 1 and 2 are cyanobacteria-dominated whereas Type 3 crusts are made up of both cyanobacteria and surface lichen communities (Thomas and Dougill, 2007). The order of their fragility (measured in terms of crust strength with a portable needle penetrometer) is Type 1 > Type 2 > Type 3 and the reverse order is true for their structural development and surface microtopography/roughness (see Thomas and Dougill, 2007). Intact soil cores and crust samples were collected in small petri dishes and wrapped in cotton. Cyanobacterial

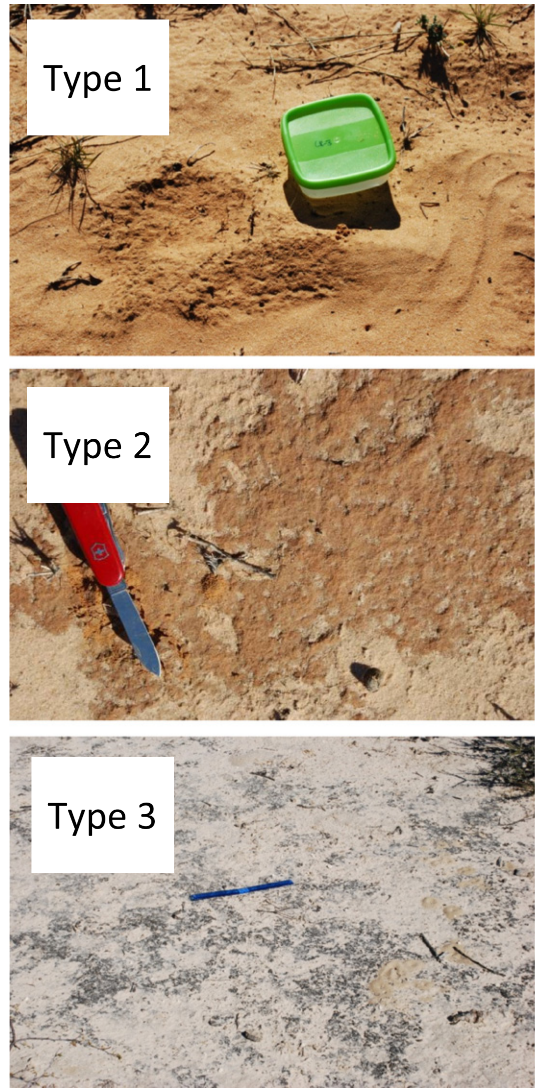

Fig. 1. Photographs showing various crusts Types (1–3) found in Kalahari. The order of their fragility is Type1 > Type2 > Type3. The Types 2 and 3 were used for this study.

Type 2 and mixed cyanobacteria–lichenous Type 3 samples were able to be packed and transported to the laboratory without breaking up and as such were used for this study. Type 1s (early development-stage cyanobacterial crusts) were not studied due to their very low compressive strength, making intact transit to a distant imaging facility was difficult to ensure.

2.2. XMT imaging

X-ray microtomography (XMT) is a non-destructive 3D imaging technique widely used for visualization and quantification of inner structure (for soil applications see review by Taina et al., 2008) without tedious sample preparation. The high resolution images obtained using XMT typically show spatial arrangement (structure) of solid particles and pores in space. The facility consists of an X-ray source, a detector and the sample in between. The XMT scanner (Phoenix Nanotom 160 NF) used for this study has a nano-focus X-ray tube, capable of producing a spot-size (akin to aperture in pin-hole imaging) of less than 1 μm, up to 180 kV tube voltage and 880 μA tube current, giving a 15 W power output. Detail detectability can go down to 200–300 nm. The CCD X-ray detector array has 2304 × 2304 pixels.

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