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# Surface indicators are correlated with soil multifunctionality in global drylands

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## Abstract

1. Multiple ecosystem functions need to be considered simultaneously to manage and protect the many ecosystem services that are essential to people and their environments.

Despite this, cost effective, tangible, relatively simple, and globally-relevant methodologies to monitor *in situ* soil multifunctionality, i.e. the provision of multiple ecosystem functions by soils, have not been tested at the global scale.

2. We combined correlation analysis and structural equation modelling to explore whether we could find easily measured, field-based indicators of soil multifunctionality (measured using functions linked to the cycling and storage of soil carbon, nitrogen, and phosphorus). To do this, we gathered soil data from 120 dryland ecosystems from five continents.

3. Two soil surface attributes measured *in situ* (litter incorporation and surface aggregate stability) were the most strongly associated with soil multifunctionality, even after accounting for geographic location and other drivers such as climate, woody cover, soil pH and soil electric conductivity. The positive relationships between surface stability and litter incorporation on soil multifunctionality was greater beneath the canopy of perennial vegetation than in adjacent, open areas devoid of vascular plants. The positive associations between surface aggregate stability and soil functions increased with increasing mean annual temperature.

4. S*ynthesis and applications*. Our findings demonstrate that a reduced suite of easily measured *in situ* soil surface attributes can be used as potential indicators of soil multifunctionality in drylands worldwide. These attributes, which relate to plant litter (origin, incorporation, cover), and surface stability, are relatively cheap and easy to assess with minimal training, allowing operators to sample many sites across widely varying climatic areas and soil types. The correlations of these variables are comparable to the influence of climate or soil, and would allow cost-effective monitoring of soil multifunctionality under changing land use and environmental conditions. This would provide important information for evaluating the ecological impacts of land degradation, desertification and climate change in drylands worldwide.

**Keywords:** Drylands, soil function, litter, nutrient function, soil attributes, soil condition, soil health, soil stability

## Introduction

Multiple ecosystem services, including food and fuel production, clean water, climate regulation and cultural and educational services are essential for sustaining human populations (Costanza et al., 1997; Adhikari & Hartemink 2016). Maintaining and monitoring the ecosystem functions that support these services, such as organic matter decomposition, nutrient cycling and soil stability, is an important societal challenge we face in response to changing climates and increasing land degradation. A wide range of indices have been proposed to monitor the physical, chemical and biological status of soils to manage them in a sustainable way (e.g. Cardoso et al. 2013; Ferris & Tuomisto 2015; Costantini et al. 2016; Pulido, Schnabel, Contador, Lozano-Parra, & Gómez-Gutiérrez 2017). Soil health indices based on laboratory analyses have also been developed for a range of systems, from agricultural and pastoral, to natural systems (Cardoso et al. 2013; de Paul Obade & Lal 2016; Franzluebbers 2016). To date, most studies of soil health indicators have been carried out at specific sites, with a few exceptions at continental or regional scales (Tongway & Hindley 2004; Pyke, Herrick, Shaver & Pellant 2002; Eldridge, Delgado-Baquerizo, Travers, Val & Oliver 2016; Molaeinasab, Bashari, Tarkesh & Mosaddeghi 2018).

Despite the large number of potential indicators used worldwide, we lack clarity on which indicators are most useful to monitor *in situ* soil multifunctionality (i.e. the ability of soils to provide multiple ecosystem functions simultaneously) at a global scale. This is particularly important in drylands, which cover almost ~45% of Earth's terrestrial surface (Prăvălie 2016), maintain ~38% of the global human population, mostly in developing countries, and are severely affected by land degradation and desertification (Cherlet et al., 2018). The identification of a simplified, cost-effective and practical suite of surface indicators to measure soil multifunctionality *in situ* would be a major advance, allowing land managers, governments and society to monitor the extent to which drylands can provide essential ecosystem services and easing the burden of evaluating the effectiveness of programs to combat land degradation and desertification under changing climates (Sommer et al. 2011; Oliva et al. 2019).

Soil surface indicators of multifunctionality could have many advantages over traditional laboratory-based methods based on soil chemical or physical tests. For example, simple proxies of multifunctionality can enable less experienced operators and those working in remote areas, or without access to equipment/technical knowledge, to survey more sites without the need for detailed, often expensive, laboratory tests and analyses (Eldridge & Delgado-Baquerizo 2018). Simple surface indicators have been shown to be highly correlated with single groups of soil functions such as mineralisable N, and the activity of enzymes associated with carbon (C), nitrogen (N) and phosphorus (P) functioning in drylands from around the world (Maestre & Puche 2009; Rezaei et al. 2006; Vandandorj, Eldridge, Travers, & Delgado-Baquerizo 2017; Eldridge & Delgado-Baquerizo 2018). The simplicity of use and low cost of these soil surface attributes have resulted in an increase in the adoption of simple soil health indicators over the past few decades by managers and environmental agencies (Cardoso et al. 2013; Pulido et al. 2017). This is particularly true in drylands from developing countries, where monitoring extensive areas of rangelands is prohibitively expensive and where well-equipped laboratories with experienced technicians are often limited or non-existent.

Herein we report on a study conducted to develop a limited suite of soil surface attributes that are strongly tied to soil functions associated with C, N and P functioning in global drylands. We used surface attributes from the Landscape Function Analysis (LFA: Ludwig & Tongway 1995) system, which has been widely used over the past decade in drylands worldwide (e.g. Tongway 1995; Tongway & Hindley 2004; Maestre & Puche 2009; Yari, Tavili, & Zare 2012; Gaitán et al. 2018). This system is a field-based soil proxy assessment technique that incorporates a quadrat-based module (Soil Surface Condition, SSC) that allows the operator to assess health using readily identifiable soil surface features (Tongway 1995). The SSC module within LFA is based on the rapid assessment of 13 soil surface attributes (Table 1; See Appendix S1 in Supporting Information) that, when integrated, provides a measure of the capacity of the soil to undertake functions associated with hydrology (infiltration index), nutrient cycling and retention (nutrient index), and surface stability (stability index; Tongway 1995). The SSC component of LFA has been used widely to evaluate the impacts of grazing and the success of restoration on ecosystems globally, and excellent examples of such systems for evaluating ecosystem change are provided in Tongway and Hindley (2004), Tongway and Hindley (2009) and de Simonia and Leite (2019).

We posit that a limited set of soil surface attributes is associated with soil multifunctionality in drylands globally. To test this prediction, we used data from an extensive global assessment of 120 dryland ecosystems across five continents to examine the potential relationships among 13 soil surface attributes and soil multifunctionality (assessed as the average measure of functions related to C, N and P cycling, and similar indices based on separate C, N and P functioning). Drylands are prime candidates for an integrated system of soil assessment linking readily and easily discernible surface features to rigorous methods of soil functionality. This is so because drylands are prone to land degradation and desertification (Cherlet et al. 2018), and their soils are highly susceptible to sustained reductions in functions due to inappropriate land management practices, combined with climate change (Cherlet et al., 2018). Specifically, we: (a) assess the association between the 13 soil surface attributes and changes in soil multifunctionality and C, N, P cycling at a global scale, and (b) test whether these differ between vegetated and open microsites, and (c) identify those surface attributes that are specifically linked to soil multifunctionality and C, N and P cycling after accounting for other environmental variables such as differences in location, aridity, relative woody cover and soil physical and chemical properties.

## Materials and Methods

### *The study area*

Field data were collected from 120 dryland sites located in 11 countries from five continents (Argentina, Australia, Brazil, Chile, Ecuador, Morocco, Peru, Spain, Tunisia, USA and Venezuela; Appendix S2). Sites were chosen to cover a wide spectrum of abiotic (climatic, soil type, slope) and biotic (type of vegetation, total cover, species richness) features characterizing drylands worldwide. For instance, the FAO Aridity Index (AI = precipitation/potential evapotranspiration) ranged from 0.05 (Chile) to 0.70 (Venezuela), mean annual temperature from 7.1 ºC (Argentina) to 27.7 ºC (Venezuela), and seasonal precipitation (coefficient of variation; https://www.worldclim.org/bioclim; BIO15) from 66 mm (Australia) to 127 mm (Chile). For soil properties, soil C and pH ranged from 0.5% (USA) to 5.4% (Brazil), and 4.1 (Brazil) to 8.9 (USA), respectively.

### *Climatic variables*

For each site, we obtained information on mean annual temperature (MAT) and seasonal precipitation (PSEA) at 1 km resolution from the WorldClim database (www.worldclim.org) (Hijmans, Cameron, Parra, Jones, & Jarvis 2005). We also collected data on the AI from the Global Potential Evapotranspiration database (Zomer, Trabucco, Bossio, & Verchot 2008), which is based on interpolations provided by WorldClim. Since higher values of the Aridity Index correspond with more mesic (less arid) sites, we used 1-AI (hereafter ‘aridity’) as our measure of aridity (Delgado-Baquerizo et al., 2013a). Aridity was used in addition to mean annual temperature (MAT) and seasonal precipitation (PSEA) because it is a useful tool to account for spatial differences among global sites and provides a more accurate measure of the water availability at each site (Delgado-Baquerizo et al. 2013a).

*Field-based assessment of vegetation and soil surface characteristics*

At each site, we established a 30 m × 30 m plot representative of the dominant vegetation. Within this plot we established four 30 m transects, as described in Maestre et al. (2012), to calculate the relative proportion of woody vegetation cover at each site. Within the same plot we randomly selected five perennial patches dominated either by trees, shrubs or large grasses (hereafter 'vegetated' microsites) that were the most representative perennial vegetation at each site, and five interspaces devoid of perennial vegetation (hereafter 'open' microsites). When more than one dominant plant form was found, 10 vegetated microsites (five of each dominant form, e.g. grasses and shrubs) and five open microsites were selected. Within each selected microsite we placed a 50 cm by 50 cm quadrat to measure 13 soil surface attributes according to the LFA methodology (Tongway & Hindley 2004). The attributes measured were: the roughness of the soil surface (surface roughness), the force required to disrupt the crust with an index finger (crust resistance), the extent to which the soil crust was unbroken (crust brokenness), the stability of surface soil aggregates assessed using the slake test (surface stability), the cover of uneroded soil surface (surface integrity), the cover of lag material deposited on the surface (deposited material), the cover of biological soil crusts (biocrust cover), foliage (foliage cover) and basal cover of perennial plants (basal cover) surface cover of litter (litter cover), the extent to which litter was deposited *in situ* or transported from elsewhere (litter origin), the degree to which litter was incorporated into the surface soil (litter incorporation), and the texture of the soil surface (texture; Table 1, Appendix S1). These attributes are also used in other commonly applied methods of soil health that relate to how the soil resists disturbance, infiltrates water and cycles nutrients (Pyke et al., 2002; Rezaei et al. 2006; Moussa, van Rensburg, Kellner, & Bationo 2008).

*Soil and analytical procedures*

A composite sample of five, 145 $cm^3$ soil cores (0-7.5 cm depth) was collected from each 50 cm x 50 cm quadrat, bulked, and homogenized in the field. The number of soil samples varied between 10 and 15 per site, depending on the number of perennial plant patches surveyed. Air-dried soil samples from all countries were shipped to Spain and analysed at the laboratories of Rey Juan Carlos (Móstoles), Jaén and Pablo de Olavide (Seville) Universities (see Maestre et al. 2012 and Delgado-Baquerizo et al. 2013b for further details).

To quantify soil functions, we measured relevant soil variables associated with C, N and P cycling and storage: organic C, pentoses, hexoses, extractable nitrate and amino acids, dissolved organic N, potential N mineralization, available (Olsen) P, phosphatase activity and total P. These variables measure either "true" functions (*sensu* Reiss, Bridle, Montoya, & Woodward 2009), such as potential N mineralization are either realistic surrogates of soil productivity and nutrient cycling (e.g. organic C and available P) or are commonly used proxies for nutrient storage (e.g. total P). They also underlie critical ecosystem process in drylands (Whitford 2002) and are related to supporting ecosystem services such as soil fertility and climate regulation (Cardoso et al. 2013). Organic C was colorimetrically evaluated after oxidation with potassium dichromate and sulphuric acid as described in Anderson & Ingram (1993). Olsen P was measured after extracting with 0.5 M $NaHCO_3$ at pH 8.5 in a 1:5 ratio, as described in Olsen et al. (1954) and Delgado-Baquerizo et al. (2013a). Total P was determined using a colorimetric determination of $PO_4^{-3}$ based on the reaction with ammonium molybdate and development of the "Molybdenum Blue" colour (Bray and Kurtz 1945). Dissolved organic C, organic C fractions (pentoses + hexoses), and inorganic and organic N forms were extracted with 0.5 M $K_2SO_4$ in a 1:5 ratio. Phosphatase activity was measured by determining the release of p-nitrophenol from p-nitrophenyl phosphate in 4-methylumbelliferone (MUB) buffer at pH 6.5 as described in Delgado-Baquerizo et al. (2013a). Potential net N mineralization (production of inorganic-N) rates were measured by determining the total available N before and after incubation in the laboratory at 80% of water holding capacity and 30ºC for 14 days (Delgado-Baquerizo & Gallardo 2011).

*Measures of soil functioning*

We developed four measures of soil functioning based on the average of standardised (*z*-transformed) values for the set of laboratory measured soil functions: C functioning index (organic carbon, hexoses and pentoses), N functioning index (nitrate, dissolved organic nitrogen, amino acids and potential nitrogen transformation rate), P functioning index (available phosphorus, phosphatase and total phosphorus), and overall soil multifunctionality index (the ten C, N and P functions; Maestre et al. 2012).

*Statistical analyses*

There were three components to our analyses, which directly explored: 1) correlations among the 13 soil surface attributes, and with soil multifunctionality and C, N and P functioning indices, 2) whether the 13 soil surface attributes varied between vegetated and open microsites, and 3) the direct and indirect relationships between selected soil surface condition attributes on soil multifunctionality and C, N and P functioning indices, using structural equation modelling. Prior to any of these analyses, we 'pre-treated' the data to account for any potential confounding caused by differences among geographical areas. We first separated our data into those from vegetated ($n$ = 156) and open ($n$ = 130) microsites. To reduce potential effects of different countries, we subtracted from each predictor and response variable the difference between the country mean and the grand mean for that variable, resulting in a 'centred' dataset, releasing any regression relationship from possible geographical area effects (see Cole, Koen, Prober, & Lunt 2018). We did this separately for data from vegetated and open microsites. Any natural variation among samples remains inherent in the data after this 'centring' process but differences among countries are removed, allowing us to focus on detection of patterns that apply universally within the countries studied. All subsequent analyses were performed using centred variables.

We then used Spearman's *rho* correlations to test potential correlation among the 13 surface attributes (Table S3) and then correlated them with the three functionality indices (C, N, P) and soil multifunctionality, and found 14 and 11 significant correlations for vegetated and open microsites, respectively (Table S3). To explore potential differences in the 13 surface attributes between vegetated and open microsites we undertook three analyses. First, for each attribute, we used linear mixed models, with microsite as a fixed factor and site ($n$ = 130) as a random effect. The analysis had two strata to account for the nesting of microsites within sites. The first stratum of the linear model examined country ($n$ = 11) effects, and the second stratum microsite (vegetated vs. open) and its interaction with country. Second, we used non-metric multidimensional scaling ordination (MDS) on a Euclidean distance matrix in PERMANOVA (Anderson 2001) to explore multivariate differences between the two microsites using data on the 13 surface attributes with the same mixed models analytical structure described above. PERMANOVA and MDS analyses were done using PRIMER-E Ltd. & PERMANOVA version 6. To interpret the MDS biplot, we correlated the values of the first two dimensions of the MDS biplot, separately, with values of each of the 13 surface attributes.

For the third analysis, we selected those soil surface attributes that were correlated with at least two of the four soil functioning indices, for either vegetated or open microsites, to conduct structural equation modelling analyses (Grace 2006). Structural equation modelling (SEM) tests the plausibility of a causal model, based on *a priori* information, in explaining the relationships among a group of variables of interest. There were six attributes (litter cover, litter origin, litter incorporation, plant foliage cover, surface stability, and surface brokenness), which were used in our *a priori* SEM model. This model aimed to examine potential relationships among these attributes and soil multifunctionality and C, N and P functioning indices, while accounting for any effects of differences in climate, relative woody cover, and soil chemistry (i.e., soil pH and electrical conductivity) among sites (Fig. S4). Potential mechanisms underlying our *a priori* pathways are presented in Table S4. To account for the spatial correlation found in our data, we also included Location in the SEM analyses as a composite variable comprising latitude, cosine longitude and sine longitude. Both microsites were included in a single SEM analysis to avoid results that were restricted to one microsite only, as this would have reduced the utility of our results, given that dryland sites contain a mixture of both microsites. Our *a priori* model was compared with the variance-covariance matrix to assess an overall goodness-of-fit, using the $\chi^2$ statistic. The goodness of fit test estimates the long-term probability of the observed data given the *a priori* model structure (Appendix S3), indicating whether the models are highly plausible causal structures underlying the observed correlations. We conducted our analyses with the AMOS 20 (IBM, Chicago, IL, USA) software.

## Results

The 13 soil surface attributes evaluated showed a wide range of variation across the studied sites (Table 2), a consequence of using both globally-distributed locations and contrasting (vegetation and open) microsites. We detected substantial differences between microsites after accounting for regional differences and the nesting of microsites within sites (pseudo $F_{1,145} = 56.7$; $P$ (perm) = 0.001; Fig. 1). For example, vegetated microsites were rougher, and more resistant to penetration, and exhibited greater surface integrity (i.e. showed less erosion). Litter cover was not only greater, but more incorporated and locally derived (Table 2). There was no difference in biocrust cover or crust brokenness across microsite. All this is critical for testing our research question, which requires both a wide gradient in soil surface condition and multiple ecosystem functions.

*Correlations among soil surface attributes and nutrient functions*

We found a number of significant correlations among the 13 soil surface attributes (Appendix S4) and the soil multifunctionality and C, N and P functioning indices measured (Table 3). Surface stability was significantly positively correlated with all functions in both microsites except P functioning in open microsites. Litter incorporation was positively correlated with all functions in vegetated microsites, and with soil multifunctionality and C and N functioning in open microsites (Appendix S5). The positive correlations between soil multifunctionality, and litter and plant cover in vegetated microsites were absent in open microsites. Overall, apart from surface stability and litter incorporation, significant correlates of function in vegetated microsites were different from those in open microsites (Appendix S5).

*The role of soil surface attributes and other environmental variables as drivers of soil multifunctionality*

Soil pH was the strongest overall driver of soil multifunctionality (Fig. 2) and a strong driver of individual functions (Appendix S6). For soil multifunctionality, the standardised total effects (STEs) from our SEM indicated that litter incorporation and surface stability were the strongest surface attributes (Fig. 3). These results were maintained after including important factors such as location (latitude, longitude), climate, vegetation, and soil properties in our SEM. The STEs also indicated that microsite identity (vegetated microsite), relative woody cover and soil electrical conductivity were most strongly positively associated with soil multifunctionality, while seasonal precipitation was most strongly negatively associated with soil multifunctionality (Fig. 3).

Increases in litter incorporation and surface stability were directly correlated with increasing soil multifunctionality (Fig. 2). For example, sites of moderate to extensive decomposition are characterised by multiple layers of decomposing plant material ranging from fresh leaves and stems at the surface to dark humified soil at depths greater than a few centimetres. There were also some indirect effects, with part of the effect of microsite is expressed through the positive influence of microsite on litter.

Effects were also mediated by changes in climate. For example, the positive effect of aggregate stability on soil multifunctionality increased with increasing mean annual temperature and aridity. Similarly, the positive effect of soil pH on soil multifunctionality increased with increasing aridity.

For individual functions, relative woody cover had the strongest overall positive association with C functioning index, but soil pH had the strongest positive association with the N functioning index (Appendix S6). Overall, mean annual temperature and seasonal precipitation were negatively associated with the P functioning index. For C and N functions, our SEMs indicated greater function in vegetated than open microsites (Appendix S6). However, different attributes were important for different functions. For example, increasing litter incorporation and surface stability were correlated with increases in the C and N functioning indices, whereas litter origin was negatively related to C and P (Appendix S6) functioning indices. Thus, litter originating from outside the quadrat surveyed was associated with sites of greater C and P functioning indices

There were also some important indirect effects. For example, part of the effects of mean annual temperature and aridity were expressed through the positive effects of litter incorporation and stability on all functioning indices, whereas increasing seasonal precipitation had the opposite effect. Also, increasing values of litter origin increased the positive effect of soil pH on the C, N and P functioning indices whereas litter incorporation had the opposite effect (Appendix S6).

## Discussion

Our study provides evidence that a reduced suite of simple soil surface attributes could be used to monitor soil multifunctionality in dryland ecosystems worldwide. We found that four soil surface condition attributes (surface stability and litter incorporation, and to a lesser extent litter cover and origin) were strongly related to dryland soil multifunctionality and specific functions associated with the cycling and storage of C, N and P. Importantly, the major role played by these surface attributes was robust to variation in site location, relative cover of woody vegetation, temperature, precipitation, and soil pH and electrical conductivity. Significant microsite effects were apparent despite the fact that the species of shrubs, grasses and trees differed markedly across our global sites. Overall, our results suggest that as few as four surface attributes could be useful indicators in a system designed to assess soil multifunctionality across global drylands, particularly where technology is limited, and detailed laboratory methodologies are unavailable and/or not feasible.

*Litter cover and its incorporation are associated with enhanced soil multifunctionality and C functioning*

Litter was a significant driver of functionality across all functions, but litter incorporation was more strongly and consistently correlated with functions than either litter cover or origin (Figs. 2 & 3, Fig. S6). Litter is particularly important for biotically-driven functions such as those related to C and N cycling. Litter cover and incorporation represent two components of resource input from the plant to the soil system; 1) the arrangement of organic matter on the soil surface (cover, origin), and 2) the extent to which this material is incorporated into the surface soil layers (incorporation). We found that incorporation was highly correlated with all functions, even though we used a relatively crude categorical proxy of incorporation (i.e., nil, low, moderate or high). Our results are consistent with the extensive body of research showing that greater litter capture and depth are correlated with elevated concentrations of biotically-derived nutrients such as those from C and N cycling (e.g. Burke et al., 1989; Whitford 2002; Hobbie 2015). The strong link between litter cover/incorporation and soil multifunctionality is not entirely unexpected. Litter moderates surface fluctuations in soil temperature, reduces potential losses in soil moisture (e.g. Wallwork, Kamill, & Whitford, 1985; Montana, Ezcurra, Carrillo, & Delhoume, 1988; Hobbie 2015), and extends the period of time over which litter-resident micro-arthropods remain active above the surface (Cepeda-Pizarro & Whitford, 1989), thus resulting in greater soil multifunctionality. Soil organic matter has been linked to a suite of plant and soil processes such as plant growth rates, soil stability, water infiltration and nutrient mineralization rates (Lal 2004). Similarly, greater litter cover might also mean better quantity of plant inputs that will eventually lead to greater incorporation and decomposition. Moreover, decomposition of organic residues yields organism-available nutrients such as $NH^{+}_{4}$, $NO_3^{-}$, $PO_3^{-4}$, and $SO_2^{-4}$.

We also found strong negative effects of litter origin on soil P functioning index, indicating greater function associated with litter that is derived from elsewhere rather than *in situ*. This result may sound counterintuitive at first glance due to the home-field advantage hypothesis, predicting a higher rate of litter decomposition, and hence soil functioning, in the presence of indigenous litter (Ayres et al. 2009). However, water-transported woody detritus often forms large accumulations of litter ('litter dams' Mitchell & Humphries 1987; Eddy, Humphreys, Hart, Mitchell, & Fanning, 1999), which enhance surface stability and soil moisture (Harmon et al. 1986) and increase nutrient levels. Litter dams are often colonised by invertebrates such as ants, reinforcing the translocation of nutrient-rich soils from the surface to the subsoil (Eldridge & Pickard 1994). Our SEM further indicates that the negative association between litter origin and the C functioning index became stronger with increasing mean annual temperature. Increasing mean annual temperature would be expected to increase the breakdown and mineralisation of organic matter to increase soil multifunctionality and C functioning, provided that moisture and nitrogen are not limiting (Whitford 2002). Positive relationships between litter cover, and negative effects of litter origin, on soil multifunctionality and C functioning tended to wane with more seasonal precipitation. This suggests to us that soil multifunctionality is limited more by precipitation than by higher temperatures, possibly due to the strong coupling between seasonal precipitation and soil moisture. Our standardised total effects showed that litter incorporation had the greatest positive effect on most functional indices, but litter cover was equally important for C functioning (Fig. 3). The net effect of litter cover may also depend on litter type (e.g. whether the litter is from a N-fixing plant), digestibility, and depth (Lee et al. 2014) than absolute cover.

*Increasing soil functions are linked to stable soil surfaces*

We also found that soil multifunctionality, and C, N and P functioning indices were positively related to increasing stability of the soil surface, assessed as the capacity of the soil to resist breakdown when immersed in water (Emerson Slake Test; Emerson 1967). Greater stability was highly correlated with biocrust cover, and surfaces that were softer and more intact (i.e. less broken), and with greater incorporation of litter (Table S3). Indeed, litter cover represents the potential for nutrient acquisition and may be related more to the capacity of the soil to resist disturbance (surface integrity) and therefore its capacity to lose C by erosion.

Consistent with many empirical studies (e.g. Bowker, Belnap, Chaudhary, & Johnson 2008), surface stability in our study was linked to a greater cover of biocrusts. Biocrusts become more dominant in areas of increasing mean annual temperature and aridity, which could explain why increases in annual temperature, or declines in seasonal precipitation, were associated with positive effects of surface stability on soil multifunctionality, and C, N and P functions. Potential mechanisms accounting for greater stability include physical protection of the surface by lichens and bryophytes, capture of sediment by mosses, and greater aggregate stability provided by fungal hyphae and extra-cellular polysaccharides in cyanobacterial sheath material (Chamizo, Mugnai, Rossi, Certini, & De Philippis, 2018). Intact surfaces might be expected to have a richer community of biocrust organisms that undertake a greater number of functions associated with mineralisation of nutrients. Biocrusts have been shown to enhance water gain and reduce the rate of soil drying compared with bare surfaces (Gypser et al. 2016). Biocrusts could also promote greater function by maintaining greater water availability, by providing a refuge for bacterial and fungal communities in drylands, which would might promote highly functional microbial communities such as Acidobacteria and Bacteroidetes (Delgado-Baquerizo et al., 2018). Thus, biocrusts could lead to the development of small scale "fertility islands" by enhancing the fixation of atmospheric C and N, and P desorption from bedrock compared with crust-free sites (Delgado-Baquerizo et al. 2016; Ferrenberg, Faist, Howell, & Reed, 2018).

*Concluding remarks: can we monitor soil multifunctionality using surface indicators?*

Together, our study provides novel insights into the importance of specific surface attributes that could be useful proxies of soil multifunctionality in global drylands. However, we acknowledge that this study is based on a correlative analysis where correlations were relatively low ($< \pm 0.32$). Weak relationships, however, would be expected in such a study, which was global, and spanned a wide range of plant communities and environmental contexts. Our study extends the results of previous studies linking surface attributes and soil functioning carried out at local and regional scales to show that four attributes (surface stability, litter incorporation, litter cover, litter origin) have predictive power comparable to climate and soil. These surface attributes are easily assessed by operators with minimal training, yet have a strong empirical base, i.e. are related to rigorous and scientifically defensible methods of assessing soil nutrient status, after accounting for biotic and abiotic differences among sites (Maestre & Puche 2009, Gaitán et al. 2018, Eldridge & Delgado-Baquerizo 2018). This makes them ideal candidates for rapid assessment of dryland soil function at the whole of function level, or in relation to specific functions associated with C, N and P pools. Finally, our results suggest that increases in mean annual temperature will likely reduce the extent to which global drylands process soil C and N, presenting substantial challenges for land managers. A knowledge of the important surrogates of soil multifunctionality in drylands will enable researchers to monitor more sites more efficiently and cheaply; an important consideration as we move to a drier and hotter world.

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## Authors' contributions

D.J.E., M.D-B and F.T.M. conceived and designed the study and D.J.E. and M.D-B. analysed the data; D.J.E. led the writing of the manuscript, and all authors collected the field data, contributed critically to the drafts, and gave final approval for publication.

## Data accessibility

Data available via the Dryad Data Repository https://doi.org/10.5061/dryad.15dv41nsm (Eldridge et al. 2019)

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Table 1. Description of the 13 soil surface attributes recorded and their relevance for assessing soil functioning and health (after Tongway, 1995).

| Attribute | Description and relevance of attribute | Type and method of measurement | No of classes and range of values |
|---|---|---|---|
| Surface roughness | Surface microtopography. Rougher surfaces have a greater ability to retain resources | Qualitative<br>Visual assessment | Five depth classes:<br>small (< 3 mm) to very large (> 100 mm) |
| Crust resistance | The ability of the soil to resist erosion. More resistance soils can withstand erosion by water, wind or trampling | Quantitative<br>Resistance to penetration | Five classes:<br>fragile to very strong |
| Crust brokenness | Extent to which the soil crust is broken. Broken crusts are more susceptible to erosion | Qualitative<br>Visual assessment | Five classes:<br>Nil to intact crust |
| Surface stability | Ability of surface soil aggregates to break down in water. Stable soil fragments will stay intact with wetting | Qualitative<br>Emerson slake test | Five classes:<br>Unstable to very stable |
| Biocrust cover | The cover of surface biological crusts. Increased crust cover indicates greater stability and nutrient cycling | Quantitative continuous<br>Visual assessment | Five classes:<br>Nil to >50% cover |
| Surface integrity | 100 minus the cover of erosional features (e.g. rills, scalds, pedestals) | Quantitative categorical<br>Visual assessment | Four classes:<br>< 10 to > 50% |
| Cover of deposited | Deposited material on the surface indicates erosion from | Quantitative | Four classes: |

| | | | |
|---|---|---|---|
| material | nearby | Visual assessment | < 5% to > 50% |
| Plant foliage cover | Percentage of soil surface covered by plant foliage. Indicates how foliage protects the soil from rainsplash | Quantitative<br>Visual assessment | Five classes:<br>≤ 1% to > 50% |
| Plant basal cover | Percentage of the surface covered by plant stems. Indicates stability and potential nutrient cyclings | Quantitative<br>Visual assessment | Four classes:<br>< 1% to > 20% |
| Litter cover | Percentage and thickness of litter cover on soil | Quantitative<br>Visual assessment | Ten classes: < 10% (< 1 mm) to 100% (>170 mm) |
| Litter origin | Assessment of whether litter is local or has been transported from elsewhere | Qualitative<br>Visual assessment | Two classes:<br>Local or transported |
| Litter incorporation | The degree to which the litter has become incorporated into the soil | Qualitative<br>Visual assessment | Four classes:<br>Nil to extensive |
| Soil clay | The percentage of clay in the surface soil | Qualitative<br>Bolus technique | Four classes:<br>Sand (=1) to clay (=4) |

Table 2. Mean (± SE) values of the 13 soil surface attributes measured for vegetated and open microsites. Different superscripts indicate a significant different in that attribute between the two microsites at $P < 0.05$.

| **Soil surface attribute** | **Vegetated microsites ($n$ = 156)** | | **Open microsites ($n$ = 130)** | |
|---|---|---|---|---|
| | **Mean** | **SE** | **Mean** | **SE** |
| Surface roughness | 2.69[a] | 0.050 | 1.89[b] | 0.060 |
| Crust resistance | 6.82[a] | 0.203 | 5.80[b] | 0.256 |
| Crust brokenness | 2.66[a] | 0.098 | 2.47[a] | 0.111 |
| Surface stability | 2.20[a] | 0.090 | 2.11[b] | 0.094 |
| Biocrust cover | 1.54[a] | 0.070 | 1.69[a] | 0.089 |
| Surface integrity | 3.22[a] | 0.062 | 3.00[b] | 0.076 |
| Deposited materials | 3.12[a] | 0.066 | 3.26[b] | 0.069 |
| Plant foliage cover | 4.10[a] | 0.083 | 2.54[b] | 0.110 |
| Plant basal cover | 3.39[a] | 0.078 | 1.50[b] | 0.060 |
| Litter cover | 3.49[a] | 0.125 | 1.55[b] | 0.077 |
| Litter origin | 1.36[a] | 0.017 | 1.16[b] | 0.018 |
| Litter incorporation | 1.36[a] | 0.016 | 1.14[b] | 0.017 |
| Soil clay content | 3.03[a] | 0.072 | 2.93[b] | 0.082 |

Table 3. Significant ($P < 0.05$) correlations (Spearman's *rho*) among the 13 soil surface attributes and soil multifunctionality, and carbon, nitrogen and phosphorus functioning indices for vegetated ($n$ = 156) and bare ($n$ = 130) microsites. Significant ($P < 0.05$) correlations are underlines, and only those attributes with one or more significant correlation are shown.

| **Attribute** | **Multifunctionality** | **Carbon** | **Nitrogen** | **Phosphorus** |
|---|---|---|---|---|
| **Vegetated microsites** | | | | |
| Surface stability | 0.27 | 0.19 | 0.18 | 0.31 |
| Litter incorporation | 0.26 | 0.21 | 0.20 | 0.23 |
| Litter cover | 0.14 | 0.19 | 0.26 | -0.09 |
| Plant cover | 0.17 | 0.15 | 0.20 | 0.17 |
| Litter origin | -0.13 | -0.19 | 0.05 | 0.01 |
| **Open microsites** | | | | |
| Surface stability | 0.21 | 0.22 | 0.21 | 0.11 |
| Litter incorporation | 0.22 | 0.21 | 0.17 | 0.24 |
| Surface brokenness | 0.17 | 0.03 | 0.16 | 0.29 |
| Litter origin | 0.10 | 0.13 | 0.15 | 0.23 |
| Basal cover | 0.13 | 0.14 | 0 | 0.11 |
| Surface integrity | -0.11 | -0.06 | -0.22 | -0.11 |
| Surface resistance | 0.01 | 0.05 | -0.20 | 0.02 |

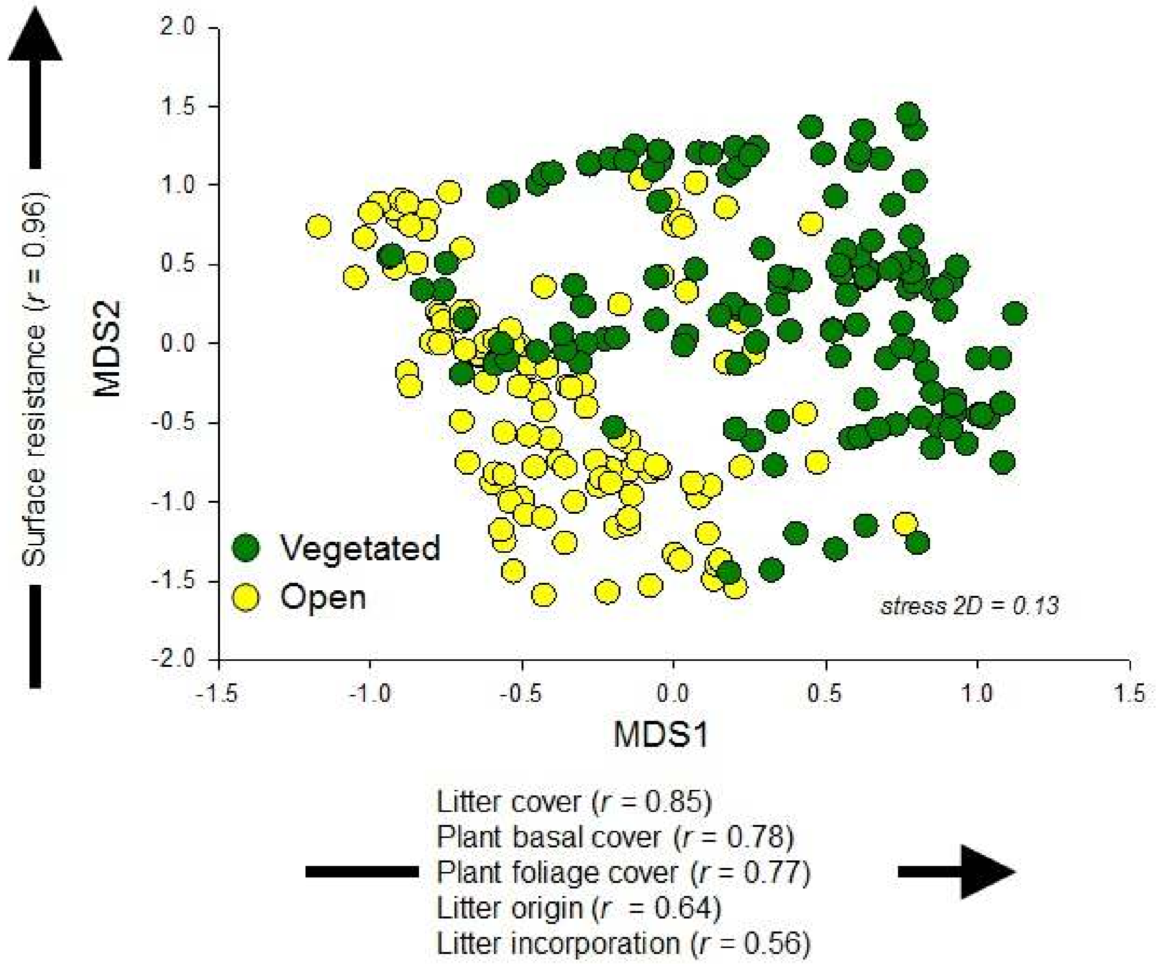


Figure 1. The first two dimensions of the multi-dimensional scaling biplot based on the 13 soil surface attributes evaluated. The correlations of plant basal and foliage cover, and litter cover, origin and incorporation with vegetated microsites were highly positive Spearman's *rho* correlations between surface attributes and the axis are given. Stress = 0.12 indicates that the data can adequately be represented in two dimensions.

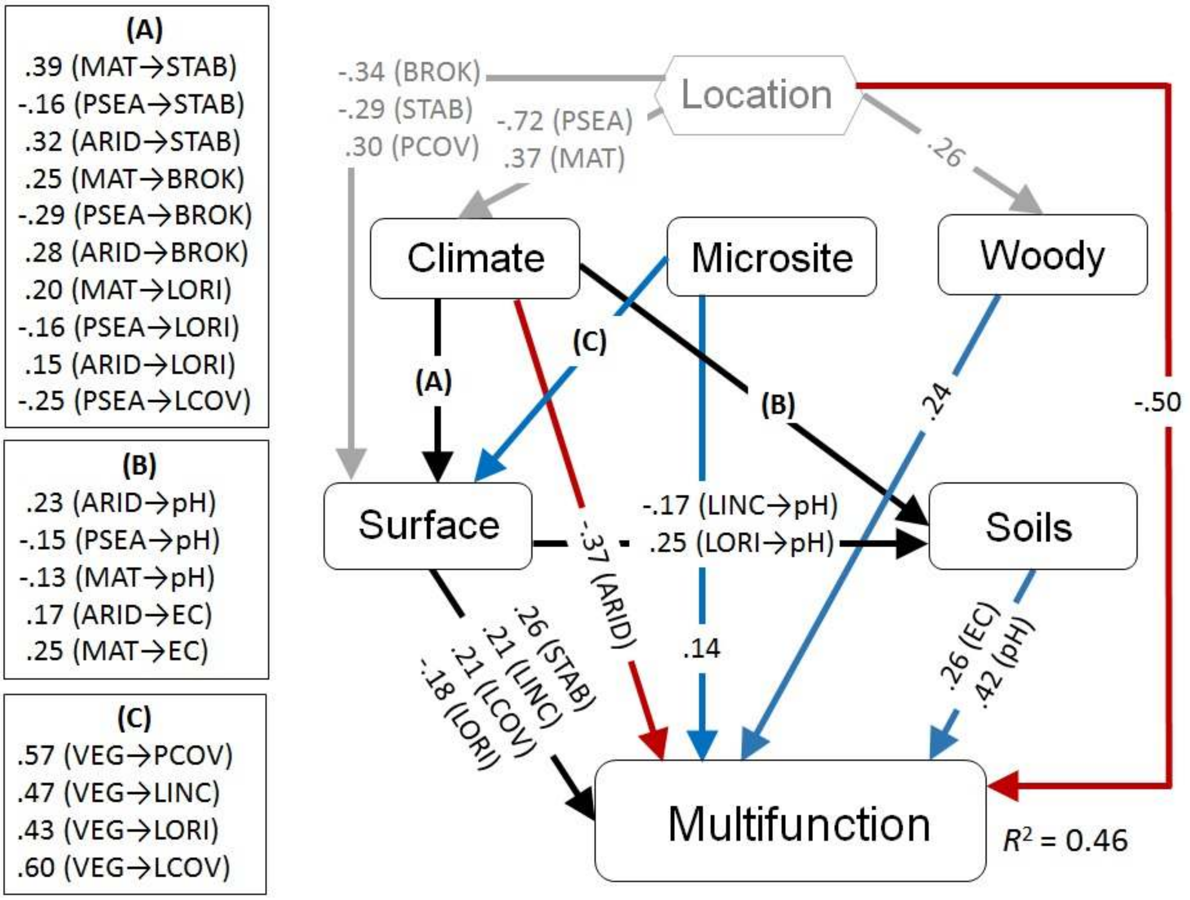


Figure 2. Structural equation model describing the effects of multiple drivers, Location (Latitude, Cosine longitude, Sine longitude), Climate (seasonal precipitation – PSEA; aridity – ARID; mean annual temperature – MAT), Microsite (vegetated [1] *vs.* Open [0] patches), Woody (relative woody cover), Soils (electrical conductivity – EC; soil pH – pH), and soil surface attributes (see Table 1) on soil multifunctionality. LCOV = litter cover, LINC = litter incorporation, LORI = litter origin, PCOV = plant foliage cover, STAB = surface stability, BROK = crust brokenness. The numbers adjacent to arrows are path coefficients, which are analogous to partial correlation coefficients and indicative of the effect size of the relationship and may be positive (blue), negative (red) or mixed (black). Only significant ($P < 0.05$) pathways are shown. Pathways from Location are greyed out for clarity. $R^2$ represents the total variance in the soil multifunctionality index explained by the model. Location is the only composite variable (shown as a hexagon)

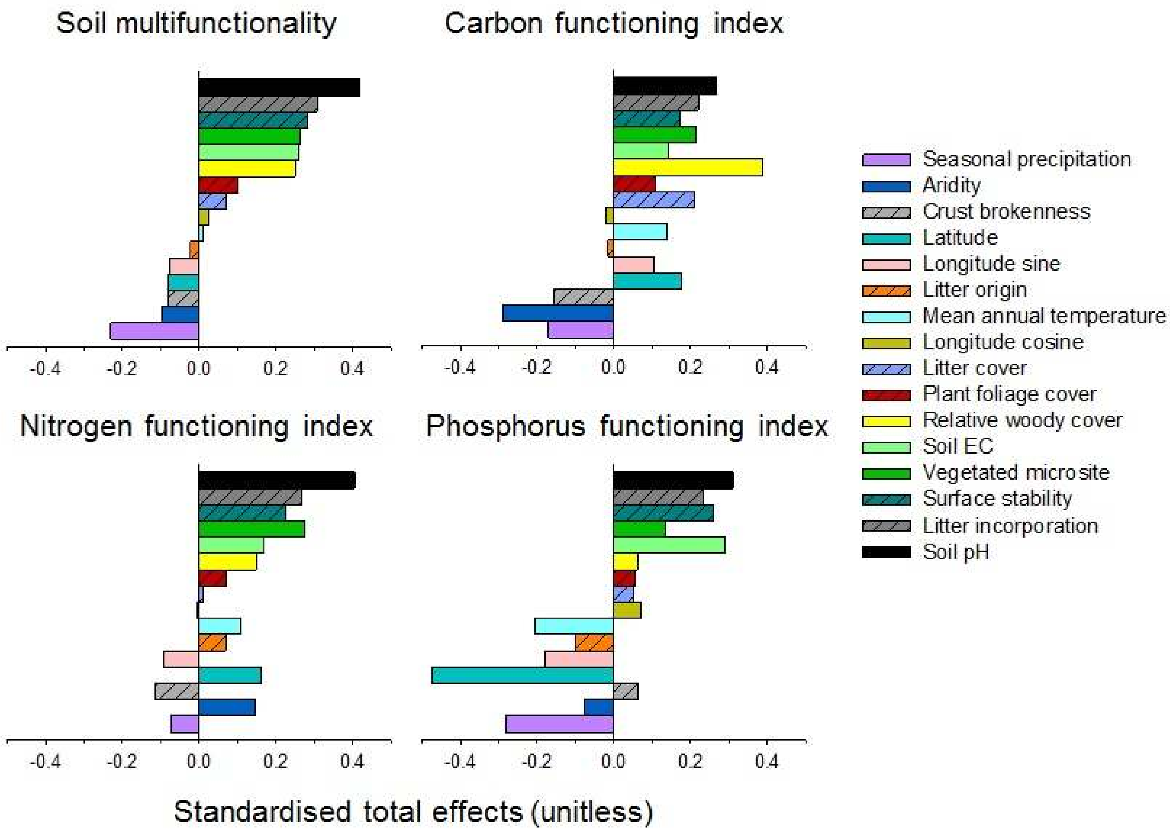


Figure 3. Standardised total effects (STE: sum of direct plus indirect effects) derived from the structural equation modelling) of Location (Latitude, Longitude sine, Longitude cosine), Climate (seasonal precipitation, aridity, mean annual temperature), Relative woody cover, Soils (EC, pH) and Microsite (vegetated *vs.* Open) and Surface (litter cover, litter incorporation, litter origin, plant foliage cover, surface stability, crust brokenness) on soil multifunctionality and soil C, N and P functioning indices. Soil surface attributes are hatched.