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# A new index to quantify dried soil layers in water-limited ecosystems: A case study on the Chinese Loess Plateau

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ABSTRACT

Soil-water deficit causes dried soil layers (DSLs) worldwide in regions covered by deep soils including soils typically found on the Chinese Loess Plateau. Traditional indices for grading DSLs have a variety of units which may lead to inconsistent conclusions and comparisons. A new index to quantify DSLs is needed for studies in soil science, ecology, and hydrology. We proposed a new quantitative index (QI) to quantify the severity of DSLs and evaluated its utility using field data collected to a depth of 1800 cm at four sites. We then determined the spatial-temporal variation and influencing factors of the QI across the entire Loess Plateau based on data sets for 382 sites in 2008. The use of the QI decreased the influence of sampling depth and soil texture on DSL evaluation, and the inconsistency of the traditional indices in quantifying DSL severity. The comparison of traditional DSL indices and QI within the 0–1800 cm layer further verified that QI could capture the vertical changes of DSLs extent among different locations. The QIs ranged from 0.11 to 0.95 at a regional scale, with moderate variation (CV = 38%) throughout the Loess Plateau. Correlation, principal component, and minimum data set analyses showed that altitude, precipitation, normalized difference vegetation index, evaporation, land use, plant age and saturated soil water content explained, in descending order, most of the QI regional variation. A distributional map of QIs developed by using regression kriging indicated that most of the regions on the Loess Plateau had severe DSLs, especially in western part of the plateau. Land-use management (including plant age) most effectively mediated DSLs at different spatial and temporal scales. The proposed QI is expected to be widely used to characterise the overall condition of a DSL. The information on QI variation at a regional scale will be useful for reclaiming DSLs using land and vegetational management in regions around the world with deep soils.

## 1. Introduction

Soil water content (SWC) plays an important role in the restoration of vegetation, reconstruction of ecological environments, and sustainable development of ecosystems (Dekker et al., 2007; Mendham et al., 2011). Soil water content depends on the balance of water inputs (e.g. rainfall and irrigation) and outputs (e.g. evaporation, root uptake, and deep water drainage) (Chen et al., 2008b; Schulte et al., 2011; Wang et al., 2011). Global change and human activities are dramatically affecting the traditional geographical, hydrological, and ecological processes in terrestrial ecosystems (Brown, 2002; Wang et al., 2016; Zavaleta et al., 2003), which may lead to increased evapotranspiration and decreased SWC in many regions, resulting in more intense and frequent droughts (Anderegg et al., 2015; Sherwood and Fu, 2014). A drought-induced negative soil water balance will lead to soil desiccation and ultimately to the creation of a dried soil layer (DSL) in the soil profile (Li, 1983; Yang et al., 1999). The occurrence of a DSL may lead to soil quality degradation, poor vegetation growth, difficulties in forest renewal through natural seed and in reafforestation of forests and grasslands (Shangguan, 2007; Wang et al., 2011).

A DSL has three characteristics: 1) it is located within the soil profile below the depth at which annual mean rainwater infiltrates, and has a thickness of 10 m or more for some planted forests; 2) it is spatially and temporally persistent and difficult to reclaim, usually becoming worse with time, with the exceptions being during extreme rainfall which leads to recharge of the subsurface soil water via infiltration, or during

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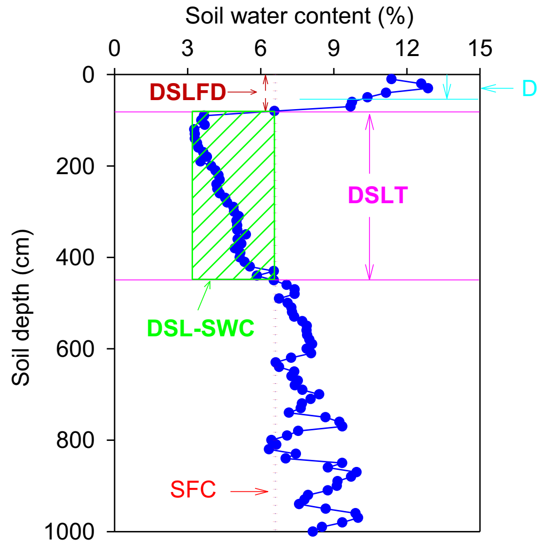


**Fig. 1.** Schematic of the three evaluation indices of dried soil layers (DSLs) in the soil profile: thickness (DSLT), formation depth (DSLFD), and mean soil-water content (DSL-SWC). In this example, soil-water data (blue) were collected on 17 October 2008 for a soil under *Caragana korshinskii* in Guyuan county, Ningxia, a semi-arid region of the Loess Plateau. SFC, stable field capacity; D, annual mean rainwater infiltration depth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changes in land use from forest/grassland to grassland/cropland; and 3) having a range of SWCs, where the upper limit of the SWC is equivalent to the "stable field capacity" (SFC, see Fig. 1) (Li, 1983; Yang and Han, 1985; Wang et al., 2011; Yan et al., 2015). According to the definition from Li (1983), the SFC represents the original soil water regime below the typical depth of infiltration from surface water, without the influence of soil evaporation and root water uptake. The value of the SFC is equivalent to 50–75% of the field capacity (FC). The SFC has a specific proportion of the FC, which is highly dependent on soil texture, with the coarser soil SFC being a lower proportion of the FC (Chen et al., 2008a). The SFC is the assumed soil moisture threshold for identifying a soil layer as a DSL (Li, 1983; Wang et al., 2011).

Three indices have generally been used to quantify a DSL: (1) the thickness of the dried soil layer (DSLT, in cm or m) (Cheng and Liu, 2014; Jia et al., 2015; Li et al., 2008; Robinson et al., 2006; Shangguan, 2007), (2) the formation depth of the dried soil layer (DSLFD, in cm or m) (Liu et al., 2010; Wang et al., 2010; Yan et al., 2015), and (3) the mean soil water content within the dried soil layer (DSL-SWC, in % or mm) (Jipp et al., 1998; Wang et al., 2012a; Wang et al., 2008; Wang et al., 2011; Zhao et al., 2007). Fig. 1 presents the schematic of the three evaluation indices of a DSL in the soil profile. The calculations of these three indices can be seen in Section 2.3.

Dry soil layers have been observed in recent decades in regions such as the Chinese Loess Plateau (CLP) (Li, 1983), Russia (Yang and Han, 1985), eastern Amazonia (Jipp et al., 1998), and southern Australia (Robinson et al., 2006). The formation of DSLs can negatively affect water cycles, crop yields (e.g. wheat), tree productivity, carbon emissions related to forest flammability and tree mortality, and the second and later rotations of plantations (e.g. *Eucalyptus globulus*) (Chen et al., 2008a; Mendham et al., 2011; Nepstad et al., 2004; Shangguan, 2007). Consequently, there is considerable interest in understanding DSL formation (Li and Huang, 2008), spatial and temporal variations (Jia et al., 2015; Wang et al., 2010), influencing factors (Yan et al., 2015), prediction models (Wang et al., 2012b), and the possibility of recovering DSLs (Huang and Gallichand, 2006).

The various DSL indices used in different studies, however, have different units (i.e. the unit is cm or m for DSLT, cm or m for DSLFD, and % or mm for DSL-SWC), which impedes the comparison of results. Moreover, the use of the current DSL indices can lead to inconsistent conclusions when evaluating DSLs. For example, Wang et al. (2010, 2011, 2012b) found that the spatial patterns of the DSL indices (i.e. DSLT, DSLFD, and DSL-SWC) differed greatly and that the factors most correlated with these indices also differed, for example, soil texture had a significant impact on DSL-SWC but a weak impact on DSLT, and root depth was closely related to DSLT but not to DSL-SWC. Jia et al. (2015) noted that DSL-SWC generally decreased from south to north along a transect on the CLP, but no obvious trend was observed for DSLT. Similarly, Yan et al. (2015) reported that the mean annual precipitation was positively correlated with DSLFD and DSL-SWC, and negatively correlated with DSLT ($P < 0.01$). These inconsistencies impede the identification of the factors contributing to DSL formation and variation. Therefore, it is difficult to (1) effectively determine the severity of the DSLs for similar terrains where the DSLT is thin but the DSL-SWC is low, or for similar soil textures where the DSLT is thicker but the DSL-SWC is relatively high, and (2) determine the dominant factors of a DSL.

Sampling to different depths (generally to 300, 500, 600, 800, and 1000 cm) when quantifying the levels of DSLs in different studies (Jia et al., 2015; Li, 1983; Li and Huang, 2008; Wang et al., 2015; Yang et al., 1999) presents another challenge. The different sampling depths may lead to different results when grading the severity of a DSL using traditional DSL indices. Developing a new DSL index that synthesizes the physical meanings of traditional indices is therefore a theory and practical requirement of DSL research in soil and hydrological sciences.

The objectives of this study were (1) to develop a new DSL index that can comprehensively quantify the severity of a DSL and to evaluate its advantages from field data collected to a depth of 1800 cm at four sites, and (2) to investigate the spatial and temporal variations of the new index and its influencing factors across the CLP.

## 2. Materials and methods

### 2.1. Study area

This study was conducted across the entire CLP (~620,000 km$^2$), which is a typical water-limited terrestrial ecosystem. The CLP has a continental monsoon climate with a mean annual precipitation ranging from 150 mm in the northwest to 800 mm in the southeast, 55–78% of which falls between June and September (1951–2001), and the mean annual evaporation ranges from 1400 to 2000 mm. The mean annual temperature of the CLP ranges from 3.6 °C in the northwest to 14.3 °C in the southeast (Wang et al., 2011). Soil textures are coarser in the northwest and finer in the southeast, and are closely associated with the origin and patterns of the loessial deposits on the CLP (Yang et al., 1999). Vegetation zones are distributed along a southeast to northwest transect in the sequence of forest, forest-steppe, typical steppe, desert-steppe, and steppe-desert (Wang et al., 2011). The geomorphic landforms are mainly large flat surfaces known as Yuans (which have very little or no erosion), ridges, hills, and extensive steep gullies. More details of the CLP have been reported by Shi and Shao (2000) and Chen et al. (2007).

### 2.2. Data collection

Four sites were initially chosen for soil sample collection to a depth of 1800 cm, in August 2011; two in Changwu County and two in Guyuan County. The land-use types were a grain field (wheat) and an orchard (*Malus pumila* Mill.) for the two sites in Changwu and grassland (*Stipa bungeana* Trin.) and shrubland (dominated by *Caragana korshinskii* Kom. with sporadic *Armeniaca vulgaris* Lam.) for the two sites in Guyuan. Physical environmental (e.g. soil type, topography) and climatic conditions were similar between the two sites in Changwu or Guyuan, which allowed for (1) clear understanding of the extent of soil desiccation based on the knowledge obtained from the previous published articles (Chen et al., 2008a; Huang and Gallichand, 2006), and