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# Predictive mapping of soil-landscape relationships in the arid Southwest United States

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ABSTRACT

Multi-scale geospatial and absolute variation of surface and near-surface soil physical and chemical properties can be mapped and quantified by coupling digital soil mapping techniques with high resolution remote sensing products. The goal of this research was to advance data-driven digital soil mapping techniques by developing an approach that can integrate multi-scale digital surface topography and reflectance-derived remote sensing products, and characterize multi-scale soil-landscape relations of Quaternary alluvial and eolian deposits. The study area spanned the arid landscape encompassed by the Barry M. Goldwater Range West (BMGRW), which is administered by the Marine Corps Air Station Yuma, in southwestern Arizona, USA. An iterative principal component analysis (iPCA) was implemented for LiDAR elevation- and Landsat ETM + -derived soil predictors, termed environmental covariates. Principal components that characterize > 95% of covariate space variability were then integrated and classified using an ISODATA (Iterative Self-Organizing Data) unsupervised technique. The classified map was further segmented into polygons based on a region growing algorithm, yielding multi-scale maps of soil-landscape relations that were compared with maps of soil landforms identified from aerial photographs, satellite images and field observation. The approach identified and mapped the spatial variability of soil-landscape relationships in alluvial and eolian deposits and illustrated the applicability of coupling covariate selection and integration by iPCA, ISODATA classification of integrated data layers, and image segmentation for effective spatial prediction of soil–landscape characteristics. The approach developed here is data-driven, applicable for multi-scale mapping, allows incorporation of a wide variety of covariates, and maps spatially homogenous soil-landscape units that are necessary for hydrologic models, land and ecosystem management decisions, and hazard assessment.

## 1. Introduction

Soil maps are valuable tools for natural resource and agricultural management; soil erosion and hydrology models; quantifying biophysical and biogeochemical functioning and landscape evolution; and assessment of natural hazards (i.e., flood, dust) that impact life, environment and property (Carre et al., 2007; Chen et al., 2011; Duffera et al., 2007; Peschel et al., 2006). Quantitative prediction and representation of soil properties and soil-landscape relationships is essential to characterizing spatial variability of the soil resource and understanding the coevolution of soils and landscapes. Approaches for characterizing soil spatial variability range from site-specific conventional survey, a combination of conventional survey with choropleth and thematic mapping, to digital soil mapping (DSM) (Grunwald et al., 2011; McBratney et al., 2003; Minasny and McBratney, 2016; Scull et al., 2003b). DSM generally uses a factorial or environmental covariate approach to prediction and spatial interpolation of observed soil attributes (e.g., regression-kriging)(Hengl et al., 2007a; Hengl et al., 2004), establishing statistical relationships of observed soil attributes with digital elevation model (DEM) derived topographic variables (Gessler et al., 1995; Hengl et al., 2007b; McKenzie and Ryan, 1999; Ziadat, 2005), remotely sensed images (Carre and Girard, 2002; Eldeiry and Garcia, 2008; Eldeiry and Garcia, 2010; Hengl et al., 2007a; Neild et al., 2007), or a combination of the two (Levi and Rasmussen, 2014; Scull et al., 2003a). Here we apply a DSM approach to characterize soil-landscape relationships across a 3200 $km^2$ desert landscape in the Southwest U.S. that spans a range of lithology, topography, vegetation, and surface processes in order to better understand Quaternary soil-landscape evolution and resulting spatial patterns in soil variability. The landscape is dominated by a set of alluvial and eolian deposits that document a complex history of climate variation, sediment redistribution, and soil development.

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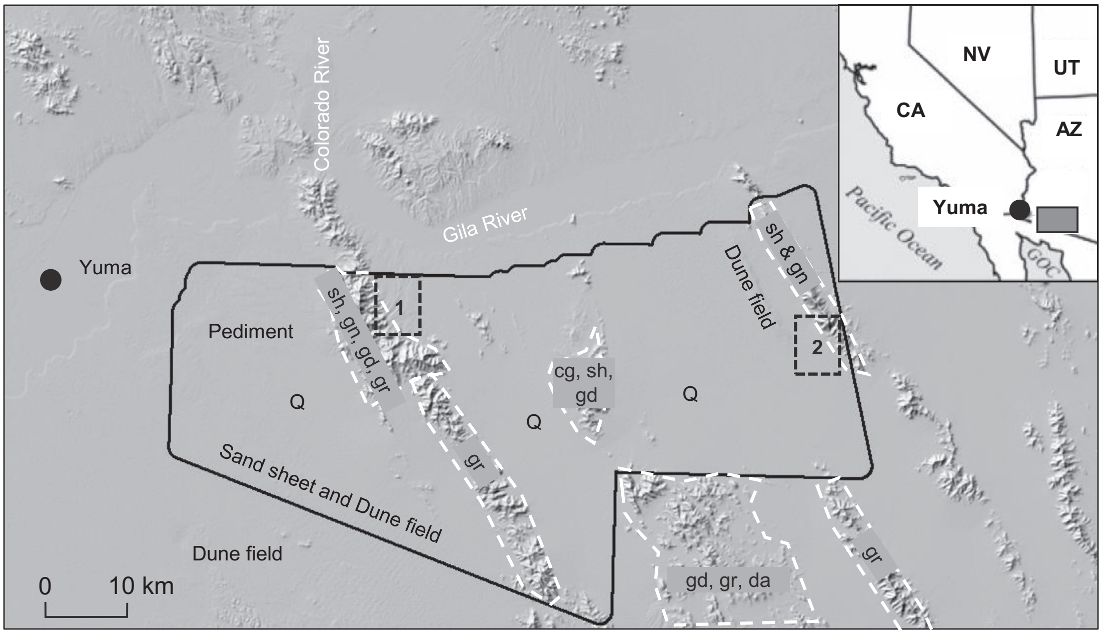


**Fig. 1.** Location of the study area near Yuma, Arizona. The area is dominated by Quaternary alluvial and eolian deposits (Q). Upland mountains consist of schist (sh), gneiss (gn), granite (gr) granodiorite (gd), and dacite (da). Areas covered by dashed rectangles (1 & 2) studied in detail.

Alluvial fans, conically-shaped deposits of fluvial and debris-flow sediments, and eolian deposits, such as sand sheets, eolian terraces and dune fields, across deserts of North America have long been recognized as an important record of Quaternary climate and tectonic activity (Bacon et al., 2010; Bull, 1991b; Gilbert, 1877; McDonald et al., 2003; Nichols et al., 2006; Wallace, 1977; Wells et al., 1987; Whipple and Dunne, 1992). The spatial distribution and stratigraphy of these deposits play a critical role in deciphering Quaternary geologic history, as well as elucidating key soil and ecosystem processes (McDonald et al., 2003; Sweeney et al., 2011). Alluvial fans and eolian deposits form through a combination of fluvial and eolian processes that result in topographic, particle size, and soil moisture gradients down the fan surface (Whipple and Dunne, 1992), that evolve and change with time (McDonald, 1994; McDonald et al., 1996; Regmi et al., 2014).

Alluvial fans of different ages can be stratigraphically subdivided by their local relief or height above the active channel, degree of dissection, drainage pattern, surface and sub-surface soil characteristics, development of desert pavement and varnish accumulation, and surface roughness (Bacon et al., 2010; Bull, 1991a; Christenson and Purcell, 1985; McDonald et al., 2003; Mcfadden et al., 1989; Regmi et al., 2014). Surface roughness of alluvial deposits tends to decrease with increasing age as a result of weathering and soil formation, dust accumulation, and desert pavement development, in addition to the evolution of channel networks from distributary patterns in younger fans to dendritic patterns in older fans (Frankel and Dolan, 2007; Regmi et al., 2014). Soils on fan surfaces exhibit general trends in development of soil properties over time, including accumulation of secondary clay minerals and calcium carbonate in surface and subsurface horizons (McDonald et al., 1996; Mcfadden et al., 1986), with the oldest surfaces generally expressing well-developed clay-enriched argillic horizons and calcic or petrocalcic horizons (also known colloquially as caliche).

Traditional soil geomorphic or soil-landscape mapping takes advantage of these clear trends in surface roughness, drainage patterns, and soil development to quantify spatial patterns of soil properties and soil-landscape relationships (Bacon et al., 2010; Frankel and Dolan, 2007; McDonald et al., 2003; Pelletier et al., 2005; Regmi et al., 2014; Wells et al., 2014). Generally, these approaches are based on observation of the surface topographic texture and tone in remote sensing products, and field observation of surface and subsurface soil, desert pavement development and varnish accumulation. Here we apply a data-driven DSM approach that couples both high resolution surface topography and texture observed on LiDAR topographic data (Frankel and Dolan, 2007; Regmi et al., 2014), with remotely sensed images characterizing surface and near-surface soil chemistry and vegetative cover (Bull, 1991a) to develop maps of soil classes across a range of spatial scales. We define soil classes as landscape units that exhibit similar surface morphological, tonal and textural characteristics. We consider identification of such landscape units of spatially similar characteristics, is possible by employing an algorithm, such as ISODATA classification techniques, that determines clusters of pixels with similar environmental covariates that measure both surface topography and soil properties (Table 2).

The objective of this study was to compare the efficacy of using a DSM approach to mapping soil-landscape relationships relative to aerial photographic interpretation based soil geomorphic approach in terms of their effectiveness for identifying soil-landscape units in the absence of extensive soil sampling and soil data. The aim of this study was also to develop base soil-landscape maps that can be used to design effective field surveys and sampling. The DSM approach applied follows Levi and Rasmussen (2014) where iterative principal component analysis (iPCA) was used to determine the topographic and reflectance data, referred to herein as environmental covariates, that explain the majority of soil-landscape variability. The resulting principal components were then classified using an Iterative Self-Organizing Data Analysis (ISODATA) unsupervised classification technique (Tou and Gonzalez, 1974; Levi and Rasmussen, 2014), followed by image segmentation of the classes to develop polygons that identify spatially homogenous soil-landscape units. The segmented polygons were compared with maps of soil-landforms developed from aerial photographic analysis and field mapping following a more traditional soil geomorphic mapping approach.

## 2. Materials and methods

### 2.1. The study area and soil characteristics

The study area is located in the Sonoran Desert in Arizona (Fig. 1). The area spans a ~3200 km$^2$ area and is comprised of Quaternary