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Digital soil mapping of sand content in arid western India through geostatistical approaches

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ABSTRACT

Digital maps of sand content of arid western India were prepared using legacy soil data published by National Bureau of Soil Survey and Land Use Planning, Nagpur following digital soil mapping (DSM) approach. In the first step, profile data was harmonized to standard depths as followed by GlobalSoilMapping programme e.g. 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and 100–200 cm using mass preserving spline tool in R. Four different approaches of DSM methodology were applied to prepare sand content map of arid western India and these are ordinary kriging (OK), universal kriging (UK)/kriging with eternal drift (KED), random forest regression and regression kriging (RK). Apart from legacy soil data, information on auxiliary and environmental variables e.g. soil map, terrain attributes and bioclimatic variables were used in the DSM methodology. Trend of covariates were fitted using random forest regression and the R^2 of fitted trend was found 0.21–0.28. The accuracy of the prepared digital products was evaluated through k-fold cross validation approach. Lin's concordance correlation coefficient (LCCC) was found 0.47–0.55 for KED, 0.45–0.51 for RK, 0.43–0.51 for random forest regression and 0.28–0.43 for OK. Apart from LCCC, other evaluation indices e.g. R^2, root mean squared error (RMSE) and bias also showed the best performance of KED to predict sand content followed by RK, random forest regression and OK. The prepared digital products will be quite useful to take decisions on appropriate and region specific soil managements. The prepared maps may further be uploaded in web map services for its wider access by end users.

1. Introduction

With advancement in data computation and information technologies, there are growing interests to apply these advanced technologies in soil science through generating soil inference system, spatial soil information system, digital soil maps etc. in different platforms e.g. desktop applications, android application, web map services etc. In addition to this, information on environmental variables and earth features are abundantly available nowadays, which may further improve the quality of digital soil maps or soil inference system. For example, digital elevation model (DEM), bioclimatic variables, proximally sensed soil spectral signatures, satellite imageries, land use/land cover information etc. have been proved as powerful tools for improvement of digital soil products As a consequence, merging of different allied subjects with soil science e.g. geographic information system (GIS), remote sensing, geography, computer science etc. has been observed and pedometrics has gained much more attention than never before. Recently it has been felt that digital soil mapping technique should enter into its operational phase from research mode throughout the world, which has also been visualized in different parts (Padarian et al., 2015; Jiang et al., 2016; Vaysse and Lagacherie, 2015; Minasny and McBratney, 2016).

Digital soil mapping (DSM) is defined as “the creation and population of spatial soil information system by the use of field and laboratory observational methods coupled with spatial and non-spatial soil inference systems” (McBratney et al., 2003; Lagacherie et al., 2006). Recently Minasny and McBratney (2016) pointed out three main components of DSM approach as reported in Lagacherie and McBratney (2006):

(i) *The input* in the form of observed soil data measured through different field and laboratory methods including legacy soil data, available soil maps and new additional soil samples using statistical sampling techniques
(ii) *The process* of building mathematical or statistical models relating soil observations with environmental covariates or ‘scorpan’ factors to create spatial and non-spatial soil inference system
(iii) *The output* in the form of spatial soil information systems including raster maps of predicted soil property and their uncertainty

Considering the above aspects of DSM approach, Grunwald (2009) reported that quantification of soil spatial pattern can be done through digital soil mapping (DSMa) and/or and digital soil modeling (DSMo)

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techniques, which in combination can be termed as digital soil mapping and modeling (DSMM). Therefore, DSM or DSMM can be divided in three approaches: (1) pedotransfer functions approach, (2) geostatistical approaches, and (3) state-factor (clorpt) approaches. In the sense of soil mapping, a pedotransfer function describes a mathematical function where one soil property is predicted by other soil properties, generally easier to measure (Bouma, 1989). Geostatistical approaches creates spatial distribution model to interpolate soil properties from point data (Krige, 1951; Matheron, 1962; Webster and Oliver, 2007). The 'clorpt' approach combines soil mapping work with other disciplines e.g. GIS, geology, environmental science, botany, ecology, meteorology etc. by quantifying or linking the relation of soil with environmental covariates and other factors, which was originally documented in soil formation theory by Dokuchaev (1883) and Jenny (1941). Later on, McBratney et al. (2003) modified the concept of 'clorpt' approach by including few other factors into it, which is called as 'scorpan' approach. In this approach, soil class or soil attributes can be viewed as a function of following factors:

$$S_c \text{or } S_a = f(s, c, o, r, p, a, n) + e$$

where S_c = Soil class, S_a = soil attribute, s = soil, other soil attributes at that point, c = climate, o = organism including anthropogenic interventions, r = relief, p = parent material, a = age, time factor and n = spatial position. Most recent works on DSM follows the 'scorpan' approach to represent the soil information system in a spatial domain.

Digital soil maps are quite different from digitized version of previously prepared soil map through soil survey where a polygon boundary represents a homogeneous soil, which has also been called us mapping unit. In the conventional approach of soil survey, soil is mapped based on surveyor's experience and field observations along with the aid of aerial photographs, remote sensing imageries, geological maps, vegetation pattern maps etc. (Hudson, 1992). All these observations were combined to draw polygons of homogeneous soil types, which are also called as the mapping units. These mapping units may be soil series, soil sub-order associations etc. Finally, the information on different soil properties for a particular soil type is attached with each polygon in the form of attribute table in a GIS environment. Earlier such type of maps are called as digital soil maps, which are labelled digitized polygon maps and such work was started in late 70's (Tomlinson, 1978; Bliss et al., 1995). Although these types of conventional soil maps are now available in digital format, these cannot be called as digital soil map but can be termed as digitized soil map. In India, National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) has been engaged in development of soil database for different states of the country and preparing soil maps through several surveying efforts during last few decades. However, there is need to convert these soil information in digital format for its wide use by different stakeholders e.g. farmers in agricultural field, researcher, policy makers etc. Keeping in view of these advancements in digital technologies and the increasing need of making soil resource information available in digital platforms, digital soil maps of hot arid western India have been prepared from available legacy soil data and maps. Ordinary kriging (OK), universal kriging (UK)/kriging with external drift (KED), random forest regression and regression kriging (RK) approaches were followed to prepare digital maps of sand contents in arid western India, which were further evaluated through cross-validation and compared with each other.

2. Materials and methods

2.1. Arid western India

Arid western India (AWI) mainly comprises the western part of Rajasthan and north-western part of Gujarata with some parts of Harynana and Punjab at its North East and East, respectively (Fig. 1). It lies between 21°17′-31°12′N and 68°8′-76°20′E covering an area of 32 million ha.

The southern, coastal part of the AWI is locally known as 'Kachch'. The central western and north-western parts of the region are dominantly covered with high and low dunes with an average height of 10–15 m, which are locally known as 'Marusthali'. The mean annual rainfall in the AWI is 400 mm. The 'Marusthali' region receives less rainfall (200–300 mm yr^{-1} with 12–15 rainy days, mostly during July–September) than the 'Kachch' region (350–450 mm yr^{-1} with 16–18 rainy days during July–September). The mean summer temperature at the 'Marusthali' region is as high as 49 °C during the day and decreases to <20 °C during the night. The mean day temperature in the coastal part of 'Kachch' is 36–38 °C, which is low compared to the western and northern plains with dune areas.

2.2. Legacy soil data from arid western India

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), India, carried out comprehensive soil surveys for different states, including Rajasthan (Shyampura et al., 2002) and Gujarata (Sharma et al., 2006), which lie in hot arid western India agroecological region of the country. The corresponding survey reports contain measured data on particle size distribution, organic carbon (OC) content (g kg^{-1}), pH, electrical conductivity (dS m^{-1}), free $CaCO_3$ content (%, g/g), soil water retention at field capacity (FC) and permanent wilting point (PWP) (%, g/g) as well as data on exchangeable bases and major nutrient contents. The soil database for arid western India (SAWI) was collated from the state level databases for Rajasthan and Gujarata by extracting those soil profiles lying within the AWI region. This yielded a total of 92 soil profiles, of which 50 were from western Rajasthan and 42 from north-western Gujarata.

2.3. Soil sub-order association map of arid western India

Soil map of arid western India was prepared from published suborder associations map of India (scale 1:70,00,000) by National Bureau of Soil Survey and Land Use Planning, Nagpur India (http://esdac.jrc.ec.europa.eu/content/soils-india-suborder-associations) (Fig. 2). Main soil types of the SAWI region, defined according to USDA Soil Taxonomy (Soil Survey Staff, 2010) include: Aridisols (37.8%), Entisols (50.1%), and Inceptisols (13.1%) (Fig. 2).

Aridisols are mainly observed in buried pediments, interdunal plains and old alluvial plains. Average depth of such profiles is 106 cm with well demarcated horizons; concretions of calcite below the soil profile are common. Psamments-Orthids are the major sub-order associations under Aridisols. Average bulk density of these soils is 1.46 Mg m^{-3} whereas average sand content is about 61%. Entisols are found in places where aeolian activity is dominant with Orthids-Psamments as major sub-order association. Average depth of Entisols is 105 cm and the bulk density is 1.54 Mg m^{-3}. Surface horizons are richer in sand content than subsurface horizons; the average sand content is 78%. Soils under Inceptisols are mainly observed at western and southern borders of arid western India with Ochrepts as the dominating soil sub-order. Average soil depth under Inceptisols is 83 cm, average sand content 51% and average clay content 34%; average bulk density is 1.51 Mg m^{-3}.

2.4. Terrain attributes of arid western India

The digital elevation model (DEM) acquired with the shuttle radar topographic mission (SRTM) with spatial resolution of 90 m around the study area was downloaded from http://srtm.csi.cgiar.org/website (Rabus et al., 2003). The SRTM DEM was pre-processed in QGIS and further used in SAGA software to calculate following terrain attributes: elevation, slope, altitude above channel network, hillshade, profile curvature, plan curvature, terrain ruggedness index (TRI) and topographic wetness index (TWI). All these derived terrain attributes in