Digital soil assessment of salinization and sodification in agricultural areas

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Abstract

Soil salinization and sodification are types of degradation due to salt accumulation in the soil. They develop in all climatic zones but are prevalent in arid and semi-arid areas. Assessment of their true occurrence is challenging owing to inadequate consideration of their evolution, lack of harmonization steps, and omission of diagnostic soil properties in the assessment. This paper developed a new assessment protocol using combined application of time-series diagnostic soil indicators, remote sensing, and environmental variables related to the occurrence of soil salts. The protocol focuses on standardization of the soil indicators, digital soil mapping, and application of classification schemes to identify levels of salt accumulation in the soil. It was tested in Lesotho, Afghanistan, and Sudan using measured soil electrical conductivity, pH, and exchangeable sodium percent, and covariates such as relief, remote sensing indicators of soil salinity, climate, hydrogeology, and land cover between 2001 and 2018. It was able to identify different types of salt-affected soils and levels of salt accumulation with over 80% accuracy on holdout samples. It identified emerging subsoil (30-100 cm) salt problems in agricultural areas in Lesotho, advancing topsoil (0-30 cm) salinization and subsoil sodification in agricultural areas in Sudan, and salinization of saline topsoils in Afghanistan. It also established important environmental covariates which can be used in periodic monitoring of salt accumulation in the soil. We recommend its wide application in different temporal and spatial scales to improve its performance in identifying salt accumulation in agricultural areas

Keywords

Salt-affected soils, salinization, sodification, degradation, soil salinity, soil assessment,

1. INTRODUCTION

Salinization and sodification are types of degradation associated with accumulation of soluble salts and/or sodium salts in the soil. Salinization occurs when soluble salts build-up in the soil while sodification occurs when there is accumulation of sodium salts. The most important salts contain carbonates (CO_3^{2-}), sulphates (SO_4^{2-}), chlorides (CL^-), bicarbonates (HCO_3^-) or nitrates (NO_3^-) of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) (Rangesamy, 2006). These salts influence soil chemical and physical characteristics in various ways. For example, they hold soil water at high osmotic potential beyond access by roots of many plants leading to water and nutrient shortage to the plants, poor plant growth, and decline in agricultural productivity. Salinization and sodification progress with time starting as a mild case and advancing to more severe problems if not corrected (Condom et al., 1999; Abrol et al., 1988). Protocols for their assessment have been widely tested in arid areas especially in salt-affected soils (SAS) (Libutti et al., 2018). However, there is scanty information on appropriate protocols for agricultural areas in regions that are not traditionally associated with SAS. There is a need for a robust assessment protocol for salinization and sodification in all agricultural soils to guide their appropriate management.

Salinization and sodification are mostly evaluated by considering increasing levels of salts in the soil after some time. Popularly used soil data for assessing the levels of salts are electrical conductivity (EC), pH, exchangeable sodium percent (ESP), sodium adsorption ratio (SAR), total soluble salts (TSS), and concentration of soluble ions (Shahid et al., 2018). Besides these soil properties, there are also alternatives in the literature for using proxy information from vegetation characteristics and remote sensing data (Gorji et al., 2019; Ivuskin et al., 2019; Scudiero et al., 2019). The target soil properties or their proxies are either used directly to monitor changes of salt levels in the soil or they are first used to classify salt levels in the soil and then the classes used to monitor changes in salt levels (Rashid et al., 2018; Chhabra, 2004). To avoid potential errors in evaluating salinization or sodification, the soil properties need harmonization. Harmonization aligns differences in measurement methods, units, etc. into uniform characteristics. Presently, there are no clear harmonization guidelines to support comparable evaluation of salt accumulation in the soil. We have attempted a harmonization protocol in this study to align different datasets into compatible characteristics to facilitate comparable evaluation of salinization or sodification.

Salinization and sodification are degradation processes that evolve with time. Therefore, their assessment needs to include aspects of time. Records of periodic evaluation of salt status to determine soil salinization or sodification are not common in the literature (Alexandre et al., 2018; FAO, 2007). This is partly due to lack of consistent time-series measured soil data for evaluating the degradation processes. Applications with remote sensing have attempted to overcome this limitation by using time-series images. The images are either correlated with discrete measurements of soil electrical conductivity or observable features of salt presence on the soil surface to assess salinization (Ivushkin et al., 2019; Matternicht & Zinck, 2003). There is no clear information in the literature on the application of remote sensing data for evaluating sodification. A robust protocol is needed to accommodate repeated assessment for evaluating salinization and sodification and incorporating the potential of remote sensing. The objective of this paper was to develop and test a protocol for identification of salinization and sodification in agricultural areas.

2. MATERIALS AND METHODS

2.1 Study areas

This study was carried out in three locations: western Afghanistan, northern Sudan, and south-western Lesotho. The study area in western Afghanistan is located between the Latitudes 30° 36’ 51.8” and 30° 12’6.64” North and the Longitudes 62° 15’55.3” and 61° 46’ 59.66” East (Figure 1). The area receives

170 mm mean annual rainfall amount and has irrigated agriculture along River Helmand. In northern Sudan, the study area stretches from the Latitude 22° 13' 30.3" to 16° 30' 28.59" North and from the Longitude 32° 41' 3.55" to 25° 0' 0" East (Figure 1). It receives 200 mm mean annual rainfall and has its agricultural areas concentrated along River Nile. In Lesotho, the study covered the whole of Mafeteng District. The district stretches from the Latitude 30° 03' 29" to 29° 31' 34.5" South and between the Longitudes 27° 49' 34.55" and 27° 16' 40.62" East (Figure 1). Mean annual rainfall in the District is 630 mm.

[Figure 1 about here]

2.2 Digital assessment of salt accumulation

We developed a three-step protocol for digital assessment of salinization and sodification in agricultural areas (Figure 2). The first step of the protocol establishes input data for assessing salt accumulation and identifies data characteristics that may need harmonization. The data is harmonized in step 2 and then used to classify levels of salt problems in the soil. Classification of salt levels is repeated for different dates of data to produce time-series information on salt problems in the soil. In step 3, the salt levels are modelled with time to identify areas with salt accumulation.

[Figure 2 about here]

2.2.1 Step 1: Input data assessment

Soil data

The input soil data used in this study were divided into two groups according to sampling dates: recently collected new dataset and old dataset (Figure 1). In Afghanistan, the old dataset was from 15 locations that were sampled in 2001. The new dataset was from 118 locations and was collected in 2018. These two datasets were randomly located in the study area and contained measured soil variables at irregular depth intervals between 0 and 100 cm from the soil surface. The soil variables were electrical conductivity (EC in dS/m), pH, texture components (sand, silt and clay in %), organic carbon (OC in %), exchangeable sodium ions (Na^+ in cmol/kg), and cation exchange capacity (CEC in cmol/kg). EC and pH were measured using electrical conductivity meter and pH meter in 1:2.5 soil extracts. Soil texture components were determined using Bouyoucos hydrometer method while organic carbon was measured using Walkley-Black method (Motsara & Roy, 2008). CEC and exchangeable sodium ions were determined according to the flame photometer method (Motsara & Roy, 2008).

In Sudan, new soil dataset was from 205 locations and the old dataset was from 213 locations. The old dataset was collected in 2004 while the new data was collected in 2018. The datasets were randomly placed in the study area and contained measured soil EC (dS/m), pH, and ESP at varying depth intervals between 0 and 200 cm from the soil surface. The soil properties were measured in saturated soil paste extracts. pH was measured with glass electrode and EC measured with a digital EC-meter (Motsara & Roy, 2008).

In Lesotho study area, new soil data was from 41 locations and old soil data was from 20 locations. The old soil data was collected in 2002 and the new data was collected in 2018. The two datasets were randomly placed in the study area. Depth sampling in the new soil data were regularly taken at 20-cm depth interval from the soil surface up to 200 cm. The old soil dataset contained soil information at irregular depth intervals between 0 and 150 cm from the soil surface. Both datasets had EC, pH, ESP, OC, and texture components (sand, silt, and clay contents in %). EC and pH were measured using conductivity and pH meters in 1:2 soil extracts. Texture components were determined according to the Bouyoucos hydrometer method while organic carbon (OC) was measured using Walkley-Black method

(Motsara & Roy, 2008). CEC (cmol/kg) and exchangeable sodium ions (cmol/kg) were measured using atomic absorption spectrophotometer (Motsara & Roy, 2008).

Exchangeable sodium percent (ESP) was calculated from exchangeable sodium ions (Na^+) and CEC as shown in Equation 1 for data from Lesotho and Afghanistan study areas.

$$ESP = ¿ \tag{1}$$

where $Ex.Na^+$ is the exchangeable sodium ions and *CEC* is cation exchange capacity. A summary of input soil data from the three study areas is given in Table 1.

[Table 1 about here]

Spatial covariates of salt-affected soils

Spatial covariates were used in modelling spatial distribution of soil EC, pH and ESP. They included maps of land cover types, soil types, geology, climate, relief, hydrogeology, and remote sensing images. Except for remote sensing images and relief, the spatial predictors were obtained from government departments in the countries of the study areas. In Afghanistan, they were obtained from the Ministry of Agriculture, Irrigation and Livestock. Here, soil types, hydrogeology, and geology data were polygon maps and climate data were 60-m resolution raster maps of mean annual rainfall amount in 2001 and 2018. In Lesotho, polygon maps of soil types, geology, and hydrogeology were obtained from the Ministry of Forestry and Soil Conservation (https://lesis.gov.ls/ , accessed on 24 January 2020). The climate were 30-m raster maps of mean annual rainfall and temperature for 2002 and 2018. In Sudan, the data were 90-m resolution maps and were obtained from GIS and Land Evaluation Unit of the Agriculture Research Centre (ARC) in Wad Madani (http://susis.sd/, accessed on 24 January 2020). The climate data were mean annual minimum and maximum temperature and mean annual rainfall amounts in 2004 and 2018.

Land cover maps were obtained from Food and Agriculture Organization (FAO) (http://www.fao.org/geonetwork/srv/en/main.home, accessed in January 2020). They were raster maps of major land cover types between 2001 and 2004 and between 2016 and 2018. The maps were classified according to the FAO land cover classification system (FAO, 2016). Remote sensing images were downloaded from https://earthexplorer.usgs.gov/ (accessed on 26th September 2019). In Lesotho, the images were multispectral Landsat images which were acquired on 20th December 2018 and 23rd December 2002. These dates corresponded with the times when there was low cloud cover over the study area. Remote sensing data for western Afghanistan study area was Landsat multispectral images, which were acquired on 7th February 2018 and on 29th January 2001. In Sudan, 8-day composite Moderate Resolution Imaging Spectroradiometer (MODIS) images were used. The images had 500 m spatial resolution and were acquired between 30th September 2018 and 1st October 2004.

All elevation maps were downloaded from https://earthexplorer.usgs.gov/ (accessed on 26th September 2019). The maps were 30-m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) images.

A GIS database consisting of input soil data and spatial covariates was established for each study area using QGIS software (QGIS Development Team, 2019). The soil data in this database was randomly split into two: one third for validation and two-thirds for calibration. The validation and calibration sets were used in steps 2 and 3 of the assessment protocol in Figure 2.

2.3.1 Step 2: Classifying salt levels in the soil

Input data harmonization

Input soil data in Afghanistan and Lesotho case studies were harmonized to the equivalent values of saturated soil paste extracts. We developed the model in Equation 2 for input soil harmonization.

$$x_h = f(x, texture, clay, OM) + error \quad (2)$$

where x_h is the equivalent value of the saturated paste extract, x is the measured value using other extracts, f is the harmonization function, *texture* is the soil textural class, *clay* is the clay content, *OM* is the organic matter content, and *error* is the modelling random error term. Clay content, textural class, and organic matter content were included in the harmonization following recommendations from the literature on their influence on EC (Kargas et al., 2018; FAO, 2006).

Soil depths were harmonized to uniform depth intervals to permit comparison of the assessment results across the study areas. We used a spline function that integrates value of the target soil property between sampled soil depths and desired depth interval for harmonization. The approach of mass-preserving splines developed by Bishop et al. (1999) was used for depth harmonization between 0-30 and 30-100 cm. These depth intervals were chosen for convenience.

Harmonization of the spatial predictors comprised remote sensing image correction, polygon map format conversion, and terrain analysis. Remote sensing images were radiometrically and geometrically corrected using semi-automatic classification plugin in QGIS software (Congedo, 2016; QGIS Development Team, 2019). Remote sensing indices of salt accumulation in the soils were calculated from corrected images as shown in Table 2 (Gorji et al., 2019). We used GIS format conversion for polygon maps such as land cover, soil, and geology maps. The maps were converted to raster images using QGIS software (QGIS Development Team, 2019). Terrain analysis of DEM images was intended to produce relief parameters such as slope, curvature, valley depth, etc. It was implemented using Basic Terrain Analysis module in SAGA GIS (Conrad et al., 2015). All the raster maps were resampled to 30-m spatial resolution in Lesotho case study, 90-m in Afghanistan case study, and 500-m spatial resolution in the Sudan case study. These spatial resolutions were chosen for convenience. Potential correlation between spatial maps was removed by taking principal component analysis (PCA) and using a set of scores for principal components which accounted for more than 97% variation in the spatial covariates (Jollife & Cadima, 2016).

[Table 2 about here]

Classification of salt problems

We used harmonized EC, pH, and ESP to classify salt problems according to the Food and Agriculture Organization of the United Nations (FAO) classification scheme (Table 3) (Abrol et al., 1988). A decision-tree model for the salt classification scheme in Equation (3) was used to classify the salt levels.

$$salt = g(EC, pH, ESP) \tag{3}$$

where *salt* is the class of salt level and *g* is the decision tree which was developed using guidelines in Table 3. Equation (3) was implemented with the *soilassessment* package of R (Omuto, 2020). In Figure 2, the input soil indicators for classifying salt levels can either be at discrete locations or as spatial maps. Discrete point classification was used for the validation soil data sets while classification of spatial maps was used to produce spatial distribution of salt problems in the study areas. The input maps were first developed using digital soil mapping (DSM) approach and the outputs used in the classification.

[Table 3 about here]

Equation 4 was used with DSM of soil properties (EC, pH, and ESP) to produce maps of the soil properties.

$$x_s = h(x_h, \Omega) + error \quad (4)$$

where x_s is the spatially modelled soil indicator, x_h is the harmonized soil indicator at discrete locations, Ω is the set of spatial predictors, *h* is the model function, and *error* is the difference between x_s and x_h. Equation (4) was developed on the calibration dataset and evaluated on the validation dataset for each study area. We used root-mean square error (RMSE), bias, correlation (R^2), and a graphical plot of predicted and harmonized values to evaluate the model's predictive performance (Krause et al., 2005).

2.3.3 Assessing salt accumulation in agricultural areas

Time-series change in soil salts was determined by modelling salt levels with time to identify agricultural areas where the salt levels changed. We hypothesised that salt classes represented certain levels of soil salts so that transition from one class to another implied changes in salt levels. Therefore, changes in salt class to a more severe class indicated increase in salt levels or salt accumulation. We indexed the degree of salt accumulation as slight, moderate, high, and very high. Slight salt accumulation represented the change from one class to an immediate class with higher salt level (Table 4). Moderate accumulation was used to index the change from one class to a higher salt level which is two classes away. High salt accumulation was used to index the change from one class to a higher salt level which is three classes away and very high salt accumulation for a transition to a higher salt level which is more than three classes away.

[Table 4 about here]

We modelled the degree of topsoil and subsoil salt accumulation in agricultural areas using Equation 5 to quantify the extent of affected soils in the agricultural areas and important spatial predictors.

$$slataccumulation = f_s(\Omega) + error \quad (5)$$

where *saltaccumulation* is the degree of salt accumulation (Table 4) and f_s is a function for modelling salt accumulation with spatial predictors of salt problems in agricultural areas.

3. RESULTS

3.1 Assessment of salt problems in the soil

Comparison of the soil indicators of salt problems in the three study areas showed that EC and pH were highest in Afghanistan study area and lowest in Lesotho study area (Table 5). The Sudan case study had the highest topsoil ESP. These characteristics portrayed the Afghanistan study area as having the most soil salinity problems and Sudan case study with the most sodicity problems. Between 2001 and 2018, values of EC and ESP seemed to have increased in the study areas. Afghanistan study area had comparatively large increase in mean EC between 2001 and 2018, which gave the impression of accumulation of saline salts during this period. Lesotho and Sudan study areas had higher increase in subsoil ESP than topsoil ESP between 2001 and 2018. Consequently, they were depicted with increase in subsoil sodic salts during this period.

[Table 5 about here]

During spatial prediction of the soil indicators of salt problems (EC, pH and ESP), we found the following spatial covariates as the most important predictors (with more than 50% variable importance):

relief parameters (e.g. slope, DEM, channel network base level, valley depth, and slope-length factor), climate variables (mean annual rainfall and maximum temperature), geology, hydrogeology, and remote sensing indices of salt problems. In Afghanistan study area, rainfall, geology, slope, valley depth, and remote sensing indices (SI5, SI2, SI4 and SI1) had more than 80% variable importance in spatial prediction of the soil properties. In the Sudan study area, geology, soil type, rainfall, temperature, slope, slope-length factor, and remote sensing indices (SI5, SI2, SI4, and SI3) had more than 75% variable importance when predicting the soil properties. In Lesotho, geology, soil type, rainfall, elevation, channel network basin level, and remote sensing indices (SI4, SI2, SI3, and SI1) had more than 90% variable importance. Overall, spatial prediction performance had more than 75% correlation with holdout samples for the tested soil properties (Table 5).

Classification of salt-affected soils in Lesotho had 100% accuracy on holdout samples and did not find any topsoil salt problems (Figure 3). The subsoils also did not have any salt problems in 2002 but showed signs of slight salinity and slight sodicity in 2018 (Figure 4). Slight salinity was classified with 1% misclassification rate and 1.7% misclassification rate for the slight sodicity class. Areas with slight salinity in 2018 were mainly in the northwest lowlands and those with slight sodicity were in the centre towards southern regions. Comparison with the soil map of Lesotho showed that the areas with slight saline subsoils were mainly in the calcareous soils and those with slight sodic subsoils were in map series described as Alfisols with probability of natric horizons (Schmitz & Rooyani, 1987). It is possible that these soil types could have influenced the observed SAS in Figure 4.

[Figure 3 about here]

[Figure 4 about here]

SAS classification in the Afghanistan study area showed that the area was generally salt affected (Figure 3). Classification of 2001 data found 60% of the topsoils and 72% of the subsoils with very strong salinity. In 2018, the classification found 30% of topsoils with very strong salinity while subsoils had 33% very strong salinity and 20% slight sodicity. These observations were reinforced by the dominant soil types which portrayed the area as SAS. The dominant soil types are Fluvic calcic Solonchaks, Calcaric regosols, and Calcaric fluvic arenosols (FAO, 2020). Overall, we found 75% classification accuracy for topsoils and 56% for subsoils. Very strong salinity class had the highest misclassification rate at 8%, which contributed to low classification accuracy in the subsoils. We attributed low spread of 2001 sampling points to high misclassification rate among very strong salinity class. In 2018, extreme salinity covered 56% of the area while very strong salinity covered 34% of the area (Figure 3). These areas had 6% SAS misclassification rate. Overall classification accuracy was 81% for topsoils and 88% for subsoil.

Overall SAS classification accuracy in the Sudan study area was 85%. Topsoil SAS covered 77% in 2004 and 86% in 2018 (Figure 3). In the north and northwest, topsoils without SAS and those with slight salinity in 2004 changed to strong salinity, slight sodicity, and slight salinity in 2018. Most of the subsoils in these areas remained with slight salinity between 2004 and 2018 except for a region which change to saline-sodic (Figure 4). These areas were covered by Calcaric Arenosols with pockets of Solonetz and Solonchaks (El Mobarak & Salih, 2013). Although the topsoils along River Nile changed from moderate and strong salinity to very strong salinity and saline-sodic (Figure 3), the subsoils remained mostly saline-sodic or slightly sodic (Figure 4). These areas were largely Fluvisols. In the southwest and east of the study area, the topsoils were mostly slightly saline in 2004 (Figure 3) but changed to moderate and strong salinity in southwest and moderate salinity and sodicity in 2018 (Figure 4). Most subsoils also remained slightly saline except in the southwest where there were pockets of strong salinity and slight sodicity in 2018. Calcisols were the dominant soil types in southwest and Leptosols and Regosols in the eastern parts. Overall, slight and moderate salinity and saline-sodic soils, which were the majority, were classified with over 80% accuracy on holdout samples.

3.2 Time-series assessment of salt accumulation

Topsoil assessment of salt accumulation in Lesotho study area between 2002 and 2018 did not find any significant increase in salt levels (0-30 cm) (Figure 5). In the same period, the subsoils showed slight salt accumulation around northwest and centre of the study area. This salt accumulation was mainly due to transition from non-affected to slight salinity in the northwest areas and transition from non-affected to slight sodicity in the central regions (Figure 4). Overall, 0.2% of the subsoils showed signs of salt accumulation.

SAS assessment in the Afghanistan study area found significant slight increase in salt levels in the topsoils between 2001 and 2018 (Figure 5). More than half of the topsoils changed from very strong salinity to extreme salinity during this period. Topsoils in the south-eastern parts along River Helmand changed from moderate salinity to very strong salinity between 2001 and 2018. Salt accumulation in subsoils were less than those in the topsoils during the same period (Figure 5). Only 12% of the subsoils showed signs of salt accumulation and were mainly in the north and along River Helmand. Most subsoils in the central parts changed the type of salts from saline to sodic salts. They were mainly soils dominated by Fluvic calcic solonchaks with possibilities of endosodic horizons in some places (FAO, 2020). It is possible that leaching in these soils left subsoil sodium ions which contributed to slight sodicity in 2018 (Figure 4).

[Figure 5 about here]

In the Sudan case study, 5% of the topsoils had high and very high salt accumulation which were mainly in the north-western parts (Figure 5). These areas changed to strong and very strong salinity in 2018 from none to slight salinity in 2004 (Figure 3). Slight to moderate topsoil salt accumulation was observed in the western parts and along River Nile (Figure 5). Moderate salt accumulation in the subsoils covered 4% of the study area while high salt accumulation covered 2%.

3.2 Salinization and sodification in agricultural areas

Lesotho case study had two areas with salt accumulation: northwest area with slight subsoil salinization and the central parts with slight subsoil sodification (Figure 5). 44% of areas with salinization and 47% of areas with sodification were in agricultural areas. The areas with salinization covered 1.1 km^2 and those with sodification covered 1 km^2 (Table 6). These areas represented a small fraction (0.1%) of the agricultural areas in the study area. Spatial predictors of salt accumulation in agricultural areas with more than 50% variable importance were soil type, mean annual rainfall amounts, slope, and remote sensing indices (SI4, SI13, and SI1).

In the Afghanistan study area, most agricultural areas were along River Helmand where irrigated agriculture is practised (Figure 1). SAS assessment found 15.9 km^2 of topsoils with salinization and 0.1 km^2 with sodification between 2004 and 2018 (Table 6). In agricultural subsoils, the assessment found 3.5 km^2 with salinization and 0.32 km^2 with sodification. Salinization was caused by slight increase in salinity from very strong salinity to extreme salinity and sodification was due to build-up of sodium salts in the lower parts of River Helmand (Figure 4). Overall, about 36% of agricultural areas showed signs of salt accumulation between 2004 and 2018. Remote sensing indices (SI5, SI4, AND SI1), geology, slope and soil type were the most important predictors of salt accumulation in agricultural areas with more than 50% variable importance.

In the Sudan case study, agricultural areas were located along River Nile where irrigation was the main source of water for agricultural activities. 28% of the agricultural areas were found with SAS, which included 712 km^2 topsoil salt accumulation and 182 km^2 subsoil salt accumulation (Table 6). Most salt accumulations were due to topsoil sodification and salinization. Salinization covered one-third of the area and two-thirds for sodification (Table 6). In the subsoils salt accumulation, more than 86% were due to salinization (Figure 4 and Table 6). Geology, soil type, remote sensing indices (SI4, SI2, and SI3), slope, and maximum temperature were the most important variables for predicting salt accumulation in agricultural areas.

[Table 6 about here]

4. DISCUSSIONS

The SAS assessment protocol in Figure 2 relies on spatial distribution of soil properties and guidelines for SAS classification, which are based on thresholds on diagnostic soil properties (Table 3). This approach was previously reported by Wicke et al. (2011) albeit at the global scale. Its application at the local scale in the three study areas produced comparable results with reports in the literature. For example, in Lesotho, Nell & van Huyssteen (2017) and Schmitz & Rooyani (1987) reported low probability of SAS in the country. There are also reports at the global scale which portray the country as a non-SAS zone (Ivushkin et al., 2019; Wicke et al., 2011; Abrol et al., 1988). These reports corroborate the results in Figure 3 and 4. The correlation between SAS areas and dominant soil types together with the mean annual rainfall (< 800 mm) could explain the occurrence of slight salinity and sodicity in the subsoils (Figure 4). Soil types and rainfall amounts were also important covariates during spatial prediction of EC and ESP. In the Afghanistan case study, the assessment results reflected reports of soil salinity in the entire western Afghanistan (FAO, 2020; Ahmadzai & Omuto, 2019). According to FAO (2020), the major soil types in western Afghanistan are Fluvic calcic Solonchaks, Calcaric regosols, and Calcaric fluvic arenosols (FAO, 2020). Western Afghanistan and Helmand River Valley have also been generally regarded as SAS zones owing to their calcareous soils and arid climate (Qadir et al., 2007; FAO, 1973; Peters, 1958). In the Sudan study area, previous studies reported varying levels of salinity and sodicity due to arid climate, irrigated agriculture along River Nile, and limestone-based geologic formations (El-Mubarak, 2009; Gebauer & Ebert, 2005). These observations mirrored the SAS assessment results in Figure 3 and 4.

The thresholds in SAS classes in Table 3 reflect thresholds on salt levels so that transition from one salt class to another implies salt level change. Salt accumulation is an example of change in salt level involving transition from a class of low salt level to a class of high salt level (Figure 5). In Lesotho, not only was there slight subsoil salt accumulation but also a salt-class change from non-SAS to slight salinity and slight sodicity (Figure 3 and Figure 4). We considered emerging salt problems to be due to slight salt accumulation in predominantly non-SAS area. In the three study areas, emerging salt problems were observed in Lesotho and southern parts of the Sudan study area (Figures 3, 4 and 5). We also considered advancing salt problem in the soil to be due to slight or moderate salt accumulation from a slight or moderate salt class. Most slight and moderate subsoil salt accumulation in the east and southeast of the Sudan study area belonged to this category of salt accumulation. The advancing salt accumulation was largely due to salinization of the subsoils. Advancing salt accumulation in agricultural areas were mainly in the southern parts along River Nile.

In the Sudan study area, the general pattern of salt accumulation decreased from west to east and southeast (Figure 5). This pattern mirrored the increasing distribution of mean annual rainfall amounts and decreasing maximum temperature from west to east and southeast. The soil types are Calcaric arenosols and Solonchaks in the west and northwest and Calcisols and Fluvisols in the east and the south (http://susis.sd/ accessed on 20 June 2020). It is possible that these characteristics provided necessary leaching which favoured less salt accumulation in the soils in the east and south than in the west and northwest.

Salt accumulation in Lesotho was generally negligible although it was depicted as an emerging problem in agricultural areas. This observation of emerging salt problems could have been partly due to the recent frequent drought in the country (Kamara et al., 2019; Hlalele, 2017; Showers, 2007) and the soil types. Persistent drought has a remarkable influence on the leaching of soil salts and potential contribution to salt accumulation in an otherwise non-SAS zone in semi-arid areas (Corwin, 2020; van der Zee et al., 2010). Afghanistan and Sudan study areas are generally regarded as SAS zones owing to their soil types and arid climate (Abrol et al., 1988). Irrigated agriculture in these areas is therefore a potential risk factor for salt accumulation. Our SAS assessment found about a third of salt accumulation in agricultural areas in the Afghanistan and Sudan case studies (Table 6). Most of the areas with salt accumulation were concentrated in the topsoils, which imply inadequate leaching of soil salts and subsequent concentration of the salts in topsoils.

5. CONCLUSIONS

This study demonstrated a protocol for SAS assessment and salt accumulation in the soil using combined application of diagnostic soil indicators, remote sensing, and environmental variables related to the occurrence of soil salts. The protocol focuses on standardization of the soil indicators to a common reference, digital soil mapping of these indicators, and application of SAS classification schemes to identify classes of salt levels in the soil. Standardization of the soil indicators supports harmonization of input data from diverse measurements and sampling for uniform time-series evaluation of soil salinization and sodification in agricultural areas.

Implementation of the protocol in Lesotho, Afghanistan, and Sudan between 2001 and 2018 was able to identify SAS and salt accumulation with over 80% accuracy on holdout samples. It showed that salt accumulation in Lesotho was not widespread like in Afghanistan and Sudan. Lesotho did not have soils with high salt content but depicted subsoil signs of emerging salt problems which need attention. Agricultural areas in Afghanistan case-study were largely affected by topsoil salinization and those in the Sudan case-study had signs of topsoil salinization and sodification. The spatial pattern of salt accumulation in these areas correlated with spatial distribution of soil types, climate, and remote sensing indices of salinity (SI1, SI4, SI2, and SI3). This correlation provided insight into environmental variables that can be used when planning inventory and monitoring of salt accumulation in agricultural areas.

The approach implemented in this study was able to identify emerging salt problems in the soil, type of salt accumulation, and advancing salt accumulation in agricultural areas. It identified emerging salt problems in agricultural areas in Lesotho and advancing salt problems in agricultural areas in the Sudan case study. Its harmonization steps enabled uniform evaluation of salt accumulation between time-series in an area and between different areas. Its wide application in different temporal and spatial scales is recommended to improve its performance.

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FIGURES CAPTION

Figure 1. Location of study areas and sampling points

Figure 2. Digital assessment of salt accumulation

Figure 3. Salt-affected topsoils between 2001 and 2018

Figure 4. Salt-affected subsoils between 2001 and 2018

Figure 5. Salt accumulation in the soil

TABLES CAPTION

Table 1 Summary of measured soil properties

Table 2 Remote sensing indices of salt problems in soil

Table 3 Classification of salt problems in soil

Table 4 Degree of salt accumulation

Table 5 Summary of spatial modelling of indicators of salt accumulations

Table 6 Salt accumulation in agricultural areas