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Assessing the effects of slope gradient and land use change on soil quality degradation through digital mapping of soil quality indices and soil loss rate

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ABSTRACT

Slope gradient and land use change are known to influence soil quality and the assessment of soil quality is important in determining sustainable land-use and soil-management practices. In this study, soil quality indices (SQIs) were developed by quantifying several soil properties to discriminate the effects of slope gradient and land use change on soil quality in 480 km^2 of agricultural land in Kurdistan Province, Iran. Three soil quality indices (SQIs) were used. Each of the soil quality indices was calculated using two linear and non-linear scoring methods and two soil indicator selection approaches, a Total Data Set (TDS) and a Minimum Data Set (MDS). Nine soil quality indicators: pH, Electrical Conductivity (EC), Organic Carbon (OC), Cation Exchange Capacity (CEC), Total Naturalized Value (TNV), Soil Erodibility (K), Porosity (P), Mean Weight Diameter (MWD), and Bulk Density (BD) and soil loss rate were measured for 110 soil samples (0–30 cm depth). Soil quality indices maps were developed using digital soil mapping methods. The > 10% slope class had the highest soil loss rate and highest percentage of soils with very low quality (grade V) based on all SQIs. The results showed that soil quality was better estimated using the Weighted Additive Soil Quality Index (SQI_w) (r^2 = 0.78) compared to SQI_a (the Additive Soil Quality Index) and SQI_n (the Nemoro Soil Quality Index). The agreement values of all SQIs for the non-linear scoring method were higher than the linear scoring method. The mean values of all SQIs and the soil loss rate were higher and lower in rangeland than cropland, respectively, but they were not significantly different because of intensive grazing. Slopes with a large gradient and where land use was converted to agriculture were characterized by low values of SQIs, suggesting a recovery of soil quality through changing to sustainable practices and abandoning over grazing in these areas.

1. Introduction

Soil quality is the capacity of soil to function to sustain plant and animal productivities, to maintain or enhance water and air quality and to support human health and habitation (Karlen et al., 1998). Soil quality attributes are strongly related to topographic properties such as slope position, slope gradient, and slope aspect (Khormali et al., 2009; Wang et al., 2009; YuanJun and Mingan, 2008). Slope gradient as a topographic factor is one of the most important factors influencing soil quality because of its effects on variations in other soil properties and crop yield (Ceddia et al., 2009; El Kateb et al., 2013; Paz-Kagan et al., 2016).

Moreover, it is well known that cultivation of the soil affects its quality (Allen et al., 2016; Khaledian et al., 2016: Oliveira et al., 2017; Rojas et al., 2016; Stevenson et al., 2015; Vinhal-Freitas et al., 2017). Conversion of natural lands to crop lands is one of the largest sources of anthropogenic carbon emissions and has led to the release of about 200 Pg C during the past 250 years, globally (Fitzsimmons et al., 2004; Scholes and Noble, 2001). Understanding of the relationships between slope gradient, land use and soil quality in catchments is needed, particularly in hilly areas.

Different methods have been developed for soil quality evaluation. Soil quality indices are a common and easy way to quantify soil quality (Andrews et al., 2002a; Qi et al., 2009) and they can improve understanding of soil ecosystems and allow more efficient management (Qi et al., 2009; Wang and Gong, 1998). Quantitative methods for calculating soil quality indices are based on using a three-step process involving: indicator selection, indicator scoring, and integration of scores into an index (Andrews et al., 2004, 2003; Larson and Pierce, 1994). Total Data Sets (TDS) and Minimum Data Sets (MDS) have been widely used to evaluate soil quality (Biswas et al., 2017; Cheng et al., 2016; Lin et al., 2017; Nakajima et al., 2015; Sanchez-Navarro et al., 2015; Sione

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et al., 2017; Yao et al., 2014). Two scoring methods are usually used to transform the selected soil indicators (Larson and Pierce, 1994). Three approaches; the Additive Soil Quality Index (SQI_a), the Weighted Additive Soil Quality Index (SQI_w), and the Nemoro Soil Quality Index (SQI_n) have been used for specific purposes and to integrate dimensionless indicators into soil quality indices (Askari and Holden, 2014; Askari et al., 2014; Biswas et al., 2017; Cheng et al., 2016; Das et al., 2016; Gong et al., 2015; Lin et al., 2017; Mukhopadhyay et al., 2014; Rahmanipour et al., 2014; Raiesi and Kabiri, 2016; Sione et al., 2017). Recently, little attempt have been made to assess the relationship between slope, land use, and soil quality indices (Askari et al., 2015; Changwony et al., 2015; Sanchez-Navarro et al., 2015; Thomazini et al., 2015; Zornoza et al., 2008), particularly in semi-arid environments.

Mapping soil quality is especially important in defining poor quality soils that occur due to high gradient slopes and land use change because the exact locations needing special management practices. Direct sampling followed by laboratory measurement is costly and time-consuming for detailed mapping of large areas. Digital soil mapping (DSM) techniques have been developed to address these issues and produce detailed maps of large areas with minimal sampling effort (McBratney et al., 2003).

The Dehgolan area located in Kurdistan province is one of the most agriculturally productive areas of Iran. Parts of the area are hilly with large gradients yet have been cultivated to feed the growing population, which has led to land degradation. Mapping soil quality can identify areas with poor quality soils for agricultural purposes due to steep gradients and can restrict agricultural use of these areas to avoid further degradation.

The main objectives of this study are: (i) to assess soil quality of agricultural land in Kurdistan Province, Iran, using two scoring methods (linear and non-linear), two methods of indicator selection (TDS and MDS) and three SQIs (SQI_a, SQI_w and SQI_n); (ii) to determine the best SQI, method of indicator selection, and scoring methods for this region and (iii) to assess the effects of slope gradient and land use change on soil quality degradation by producing digital soil quality indices and soil loss rate maps.

2. Materials and methods

2.1. Site description

The study area is located in Kurdistan Province, Iran about 20 km northeast of the city of Dehgolan and covers 480 km^2 (Fig. 1). The climate is semiarid with distinct differences between the dry and wet seasons. Average annual precipitation and temperature are 399 mm and 10.2 °C, respectively. Soil moisture and temperature regimes are Xeric and Mesic, respectively. Elevation varies from 1740 to 2845 m. The two main land uses of the study area are cropland (approximately 88%) and rangeland (determined using a 2015 Landsat image and ERDAS Imagine software) (Fig. 1). Major parent materials are limestone, marl and alluvial. The major geomorphologic units consist of piedmont, plateaus, hills, and mountains (based on a nested geomorphic hierarchy classification approach defined by Toomanian et al., 2006) and slope gradients vary from gentle to very steep (Fig. 1). The major soils of the study area (Soil Survey Staff, 2014) are Inceptisols (> 90%) and Entisols.

2.2. Soil sampling and analysis

In the study area, a total of 110 soil samples were collected (0–30 cm depth). Samples were distributed between two land uses with 15 samples taken from rangeland and 95 from cropland (Fig. 1). The samples were distributed between four slope classes with 33 samples on 0–2% slopes, 26 on 2–5%, 18 on 5–10%, and 33 on > 10% slopes (Fig. 1). Soil pH and electrical conductivity (EC) were measured in a saturated paste using a pH electrode (McLean, 1982) and conductivity meter (Rhoades, 1982). Organic carbon was determined using wet combustion (Nelson and Sommers, 1982). Cation exchange capacity (CEC) was measured using the 1 N ammonium acetate (at pH 7.0) method (Sumner and Miller, 1996). The lime content as the total neutralizing value (TNV) was determined by a volumetric method (Sparks et al., 1996). Soil bulk density (BD) and particle density (PD) were determined using both core (Grossman and Reinsch, 2002) and Pycnometer methods. Soil porosity was calculated using results from soil bulk density and partial density (Danielson and Suterland, 1986). In calcareous soils, calcium is an important factor determining aggregate stability and consequently infiltration rates that can significantly affect soil erodibility (K). Therefore, the application of Wischmeier and Smith's (1978) nomograph to calcareous soils in arid and semi-arid regions may lead to inaccurate assessment of K (Vaezi et al., 2008). Therefore the soil erodibility factor (K) was computed using Vaezi et al.'s (2008) method ((Eq. (1)).

$$K = 0.0123 - 5.7 \times 10^{-5}CC - 5.2 \times 10^{-5}TNV - 0.00192PE \quad (1)$$

where CC is clay content (%), TNV is total neutralizing value (%), PE is permeability (cm h^{-1}), and K is in t h MJ^{-1} mm^{-1}. Soil permeability was determined based on the final infiltration rate using double-ring infiltrometers (Scholten, 1997) in the field.

The method of Kemper and Rosenau (1986) was used to determine mean weight diameter (MWD) of soil aggregates using the following equation (Eq. (2)):

$$MWD = \sum_{i=1}^{n} X_i W_i \quad (2)$$

where MWD is the mean weight diameter of water stable aggregates, X_i is the mean diameter of each size fraction (mm), and W_i is the proportion of the total sample mass in the corresponding size fraction after deducing the stone mass as indicated above.

2.3. Soil quality index assessment

2.3.1. Total and minimum data set

The nine soil properties that were measured were used in a TDS and were selected for their sensitivity in soil quality evaluation. The properties: OC, BD, EC, CCE, CEC, pH, and MWD have been suggested by several authors as useful soil quality indicators because of their influence on soil fertility, supply of nutrients, pH, root growth, soil porosity, soil structure, and aggregate stability (Biswas et al., 2017; Cheng et al., 2016; Das et al., 2016; Lima et al., 2013; Mukhopadhyay et al., 2014; Qi et al., 2009; Rahmanipour et al., 2014; Sanchez-Navarro et al., 2015; Sione et al., 2017; Yao et al., 2014). Also to more accurately characterize the soils and take into account both natural processes and human impacts due to agricultural practices and land use change the soil erodibility factor was included as part of the TDS. Principal components analysis (PCA) was conducted to reduce dimensionality in the data set and determine the most important properties to include in the MDS (Doran and Parkin, 1994; Rahmanipour et al., 2014; Yao et al., 2014). For each PC with an eigenvalue > 1, soil variables with high factor loadings were assumed to be the soil properties that best represent changes in soil quality. More specifically, these were the soil properties that had absolute values within 10% of the highest factor loading (Andrews et al., 2002a; Govaerts et al., 2006; Sharma et al., 2005).

2.3.2. Indicator scoring

Each indicator/soil property from the TDS was transformed into a unitless score between 0 and 1 using both linear and non-linear scoring methods. There are three standard scoring functions (SSF) for SQIs which indicate whether the property has a 'negative' or 'positive' relationship to soil quality or if it is positively related within an 'optimum