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A spectral soil quality index (SSQI) for characterizing soil function in areas of changed land use

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ABSTRACT

During the last several decades, a large proportion of the planet's terrestrial surface has transformed from natural ecosystems to human-dominated systems. These land-use dynamics affect ecosystems' soil quality. The current study was conducted at the fringe of the northern Negev Desert, Israel, and strived to assess and compare the soil quality in three different land-use types (afforestation, traditional grazing, and agro-pastoral) that were changed from managed to unmanaged or vice versa (e.g., shrubland was transformed to a planted forest; pastoral grazing to natural shrubland with no grazing; and agro-pastoral to abandoned agricultural). The overall aim of this research is twofold: (1) to evaluate by reflectance spectroscopy the changes in 14 soil physical, biological, and chemical properties and their derived soil quality index (SQI) in the changed land uses; and (2) to develop a spectral soil quality index (SSQI) toward applying the technique of reflectance spectroscopy as a diagnostic tool of soil quality. To achieve these objectives, several mathematical/statistical procedures, consisting of a series of operations, were implemented, including a principal component analysis (PCA), a partial least squares-regression (PLS-R), and a partial least squares-discriminate analysis (PLS-DA). The PLS-R's most suitable models successfully predicted soil properties ($R^2 > 0.80$; ratio of performance to deviation (RPD) > 2.0), including sand–silt–clay content, NH_4, NO_3^-, and pH. Moderately well-predicted soil properties ($0.50 < R^2 < 0.80$; RPD > 2) were residual water, soil organic matter, electric conductivity, and potassium. Poor validation ($R^2 < 0.50$; RPD < 2) results were obtained for potential active carbon, phosphorus, and hydraulic conductivity. In addition, the PLS-R model predicted the SQI in the changed land uses. The correlations between the predicted spectral values of the calculated SQI ranged $0.65 < R^2 < 0.81$ with RPD > 2. The PLS-DA model was used to develop the SSQI model. The correlations between the SSQI and the SQI ranged $0.66 < R^2 < 0.74$ in the different land uses. This study underscores the potential application of reflectance spectroscopy as a reliable diagnostic screening tool for assessing soil quality. The classification of soils into spectral definitions provides a basis for a spatially explicit and quantitative approach for developing the SSQI. The SSQI can be used to assess hot spots of change in areas of land-use changes and to identify soil degradation.

1. Introduction

Worldwide observations have confirmed that during the last several decades, a large proportion of the planet's terrestrial surface has transformed from natural ecosystems to human-dominated systems (e.g., DeFries et al., 2004; Foley et al., 2005). These land-use dynamics are so pervasive that they significantly affect key aspects of ecosystem structures, functions, and services (Adeel et al., 2005). Accordingly, altering ecosystem services affects the ability of biological systems to support human needs (Metzger et al., 2006; Vitousek et al., 1997) and also modifies ecosystem structure and function by changing biodiversity, productivity, and soil quality (Matson et al., 1997; Tscharntke et al., 2005). Recent assessments of the ecosystem functions of soils and their importance for global sustainability underscore the importance of the management of soil resources for different land uses for present and future societal welfare (Adeel et al., 2005; Andrews et al., 2002). The concept of soil quality is related to the capacity of soil to function in supporting important ecosystem services (Idowu et al., 2009). Soil quality involves physical, biological, and chemical attributes that are merged together to indicate soil functioning (Andrews et al., 2002; Gugino et al., 2009). However, since a practical assessment of soil quality requires the integrated consideration of key soil properties and their variations in space and time, it remains a challenging task (Doran and Parkin, 1994).

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Recent studies have proposed several conceptual frameworks for monitoring soil quality (e.g., Andrews et al., 2004; Black, 1965; Stevenson, 2005; Viscarra Rossel et al., 2006). These frameworks usually share the common initial step of the choice of a minimum dataset (MDS), composed of physical, biological, and chemical properties that are essential in terms of soil functioning (Rezaei et al., 2006). The soil attributes are selected from the MDS for their suitability in assessing a particular soil function (Andrews et al., 2004), a specific soil ecosystem service (Velasquez et al., 2007), or a key threat to soils (Morvan et al., 2008). Each indicative soil property is normalized to a unitless score and, finally, integrated into a soil quality index (SQI) value (Andrews et al., 2002, 2004; Idowu et al., 2008; Karlen et al., 1997). However, because many soil analyses are involved, monitoring soil quality indices at different scales and land uses remains expensive, as well as time and labor consuming, when using the standard procedures (Cécillon et al., 2009a).

In contrast, different aspects of soil quality can be assessed by reflectance spectroscopy techniques that include visible (VIS, 400–700 nm), near-infrared (NIR, 700–1100 nm), and shortwave infrared (SWIR, 1100–2500 nm). These are rapid, non-destructive, reproducible, and cost-effective analytical methods (Ben-Dor and Banin, 1995). Reflectance and absorbance signals result from vibrations in chemical bonds and minerals that provide information about the proportion of each element in the analyzed sample (Ciurczack, 2001). Recent advances in soil analysis demonstrate that reflectance spectroscopy is a robust analytical technique suited for rapid and simultaneous analysis of the abovementioned soil attributes with various levels of prediction accuracy (Awiti et al., 2008; Cécillon et al., 2009a; Odlare et al., 2005; Velasquez et al., 2005, 2007).

Although the potential of reflectance spectroscopy as a technique for the rapid and simultaneous prediction of soil properties is rather clear, the challenge is to adapt the application of spectroscopy as a diagnostic screening tool that can aid in the development of reliable, specific spectral definitions to characterize soil quality for land management. In addition, using spectroscopy to assess the impact of changes in land use on soil properties can also help to detect environmental changes, such as soil degradation, erosion, and modifications in primary productivity. Therefore, the evaluation of soil quality, using spectroscopy as a way to generate diagnostic indices, can be used for land management. Shepherd and Walsh (2002) discussed the potential of soil spectroscopy for risk-based assessments of the effects of land use and land management on soil conditions. Vågen et al. (2006) developed a spectral fertility index and used it to investigate the effects of land use and time since forest conversion on soil conditions in Madagascar. Awiti et al. (2008) developed a spectral soil condition classification method to assess tropical forest–cropland soils in Kenya. The classification of soils that Awiti et al. (2008) developed into spectrally defined condition classes provides a basis for spatially explicit and quantitative case definitions for poor or degraded soil conditions. Such approaches need more validations, particularly to test the application of reflectance spectroscopy for detecting changes in soil condition or quality due to land management.

Our study strived to assess and compare soil quality in changed land uses using laboratory analyses of soil physical, biological, and chemical properties, as well as through spectral measurements. The overall aim of this research is twofold: (1) to evaluate the ability of reflectance spectroscopy to detect changes in soil quality across changed land uses; and (2) to develop a spectral soil quality index (SSQI) toward applying the reflectance spectroscopy technique as a diagnostic tool of land management. To achieve these objectives, several mathematical/statistical procedures, consisting of a series of operations, were used, including a principal component analysis (PCA) for establishing the SQI based on the soil physical, biological, and chemical properties (Fig. 1, step 1); a partial least squares-regression (PLS-R) to relate spectral reflectance for measuring soil properties with (SQI) scoring (Fig. 1, steps 2 and

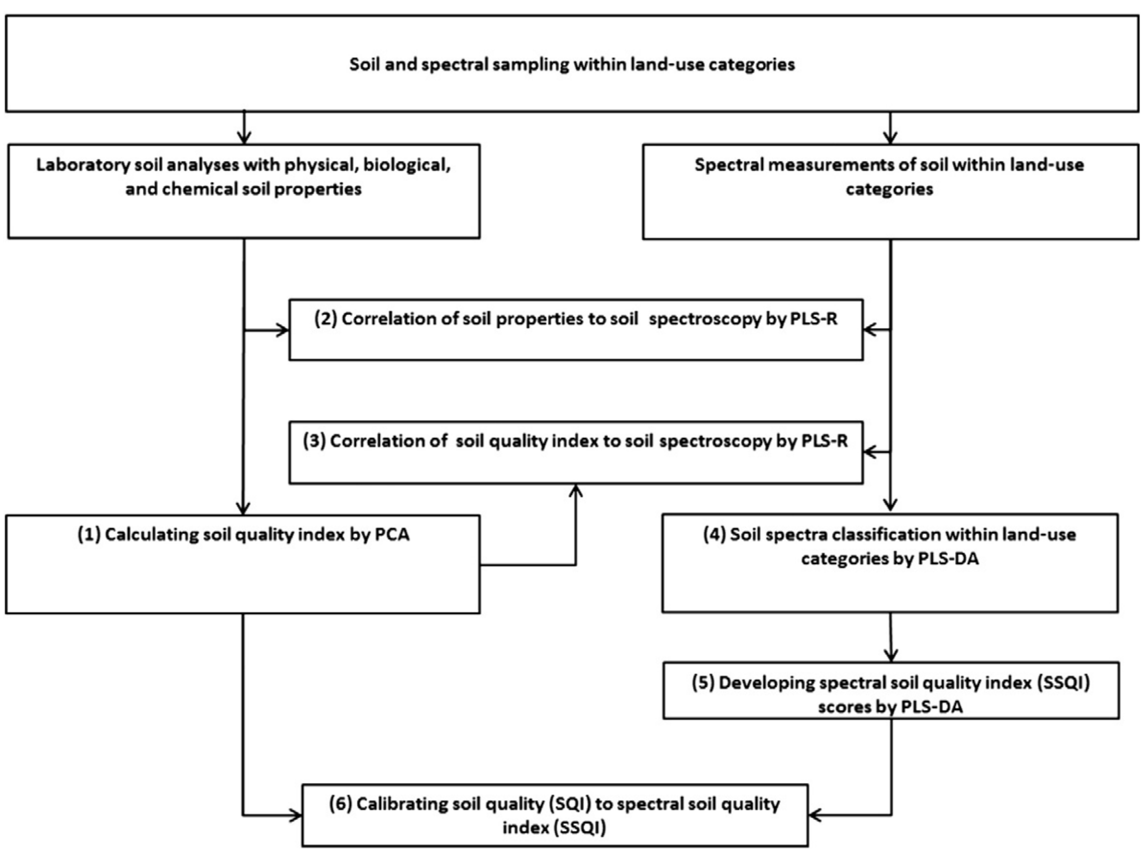

Fig. 1. The scheme for assessing the spectral soil quality index (SSQI) and the soil quality index (SQI) by laboratory and spectroscopy measurements in different land-use categories.