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Effects of land cover on ecosystem services in Tanzania: A spatial assessment of soil organic carbon

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ABSTRACT

The multiple ecosystem services provided by healthy soil are well known and include soil carbon sequestration to mitigate climate change, a medium for plant and agricultural production and regulating the hydrologic cycle. Despite the wide recognition of the importance of these services, drivers of soil organic carbon (SOC) dynamics across various land uses in East Africa are poorly understood. The objectives of this study were threefold: to quantify SOC stocks across Tanzania; assess the effect of land cover and erosion on SOC; and investigate the relationship between inherent and dynamic soil properties under diverse land uses. The Land Degradation Surveillance Framework (LDSF) was used to assess the variability of ecological metrics at different spatial scales. SOC was quantified within and between different land cover types (forest, woodland, shrubland, grassland and cropland) in Tanzania. A total of 2052 soil samples from 1082–1000 m^2 plots were collected from seven 100-km^2 sentinel sites in 2010. Composite soil samples were collected at each plot from two depths (0–20 and 20–50 cm) and cumulative soil mass samples were collected to 100 cm. Soil samples were analyzed using a combination of traditional analytical laboratory methods and mid-infrared spectroscopy (MIR). Model performance of MIR spectral predictions for carbon was good, with an R^2 of >0.95 and RMSEP of 4.3 g kg^{-1}, when using an independent validation datasets. Woodland and cropland were the most frequently occurring vegetation structure types in the sampled sites, with 388 and 246 plots, respectively. Average topsoil OC (and range) was 12.4 (1.5–81.4) g C kg^{-1} ($n = 1082$) and average subsoil OC (and range) was 7.3 (0.64–53.8) g C kg^{-1} ($n = 970$) for the seven sites. Forested plots had the highest mean topsoil organic carbon concentrations (17.3 g C kg^{-1}) followed by cropland (13.3 g C kg^{-1}), for all sites included in the study, but with high levels of variability between sites. Soil mass at 30 cm was measured and these data were used to calculate carbon stocks for the different land cover types. An approach based on remote sensing was explored for the mapping of SOC stocks at 30 cm for Tanzania using Moderate Resolution Imaging Spectroradiometer (MODIS) imagery from 2012. Results indicate that the use of image reflectance for the mapping of SOC stocks has promising potential, with R^2 values ranging from 0.77 to 0.81 and RMSEP values from 0.90 to 1.03 kg m^{-2} for the three validation datasets. There is high utility of these maps for strategic land management interventions that prioritize ecosystem services.

1. Introduction

Soil provides multiple ecosystem services, including as a medium for plant and agricultural production through maintenance of soil fertility, a filter for toxins and pollutants, a regulator of the hydrologic cycle, and potential mitigator of climate change through carbon sequestration (Brussaard, 1997; Daily et al., 1997; Lal and Bruce, 1999; Millennium Ecosystem Assessment, 2005). While the role of soil in providing these services has been documented and discussed, gaps still exist in terms of operationalizing the monitoring and quantification of these ecosystem services across diverse environments (Bello et al., 2010; Dale and Polasky, 2007; de Groot et al., 2002; Dominati et al., 2010). Globally, scientists have highlighted the importance of establishing a network of monitoring sites in order to better understand the state of natural resources, including biological diversity (Scholes et al., 2008), agricultural productivity (Sachs et al., 2010, 2012), soil properties (Makipaa et al., 2012; Richter et al., 2007; Sanchez et al., 2009; Smith et al., 2012) and land health (Vågen et al., 2012).

However, there is still a debate regarding the specific metrics to measure and monitor across space and time, as well as ways to operationalize networks of monitoring sites globally (Sachs et al., 2010, 2012; Dale and Polasky, 2007). In addition, research is still needed on the relationships between the drivers of change and the metrics

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of soil health across landscapes. However, SOC is arguably one of the most important metrics of soil health due to its contribution to well functioning ecosystems (Lal, 2010; Palm et al., 2007; Schlesinger, 1997), agricultural productivity (Lal, 2007; Miller et al., 2004; Post and Mann, 1990; Vågen et al., 2005), and its potential to mitigate climate change (Lal and Bruce, 1999), among others. The United Nations Convention to Combat Desertification (UNCCD) also stresses the importance of maintaining SOC to combat land degradation. Soil erosion is a key indicator of land degradation (Lal, 2003; Pimentel and Kounang, 1998; Vågen et al., 2013). This study aims to assess linkages between soil erosion and SOC across contrasting land cover typologies in Tanzania in order to quantify the effects of land cover on SOC, as well as interactions with soil erosion.

Soil OC dynamics have been an important research topic over the last several decades, resulting in estimates of global carbon stocks (Amundson, 2001; Jobbagy and Jackson, 2000; Post and Kwon, 2000). Other studies have focused on assessing the effects of cultivation and land use on SOC (Guo and Gifford, 2002; Miller et al., 2004; Post and Mann, 1990; Post and Kwon, 2000; Schlesinger, 1997), or understanding the complexity of SOC dynamics and climate change (Berthrong et al., 2009; Davidson et al., 2000; Johnston et al., 2004; Kirschbaum, 2000; Lal, 2004). However, gaps remain between plot-level and landscape scale assessments of SOC dynamics under different land uses, including interactions with land degradation processes.

In order to understand the drivers of changes in ecosystem health, including risks and trends over time, new tools and methods for assessing ecosystem health across diverse landscapes are needed. The Land Degradation Surveillance Framework (LDSF) is a spatially balanced, hierarchical field sampling methodology (Vågen et al., 2010a, 2010b), which has been implemented in East Africa to better understand and map land degradation indicators (Vågen et al., 2013, 2012). In addition, the LDSF has proven useful for monitoring of SOC for climate change mitigation (Vågen and Winowiecki, 2013). The current study utilizes the LDSF to assess the effects of land cover typologies on a set of soil health indicators, with an emphasis on SOC, and ecosystem services at a national scale for Tanzania, based on field sites from a diverse range of ecosystems in the country.

The overall goal of the study was to provide an example of approaches to move beyond plot-level assessments of soil and ecosystem health, which are often very detailed, and difficult to scale out beyond the domain sampled. By applying the LDSF in multiple landscapes across a wide range of climate, terrain and soil conditions and combining these measurements with remote sensing data, we show how the gap between the plot-level type assessments and coarse-scale global estimates can be bridged, focusing here on dynamic soil properties and land degradation risk factors.

Vågen and Winowiecki (2013) used Landsat ETM+ to predict SOC stocks in four case studies from East Africa, showing the potential of remote sensing for mapping of SOC at moderate to high resolution. In the

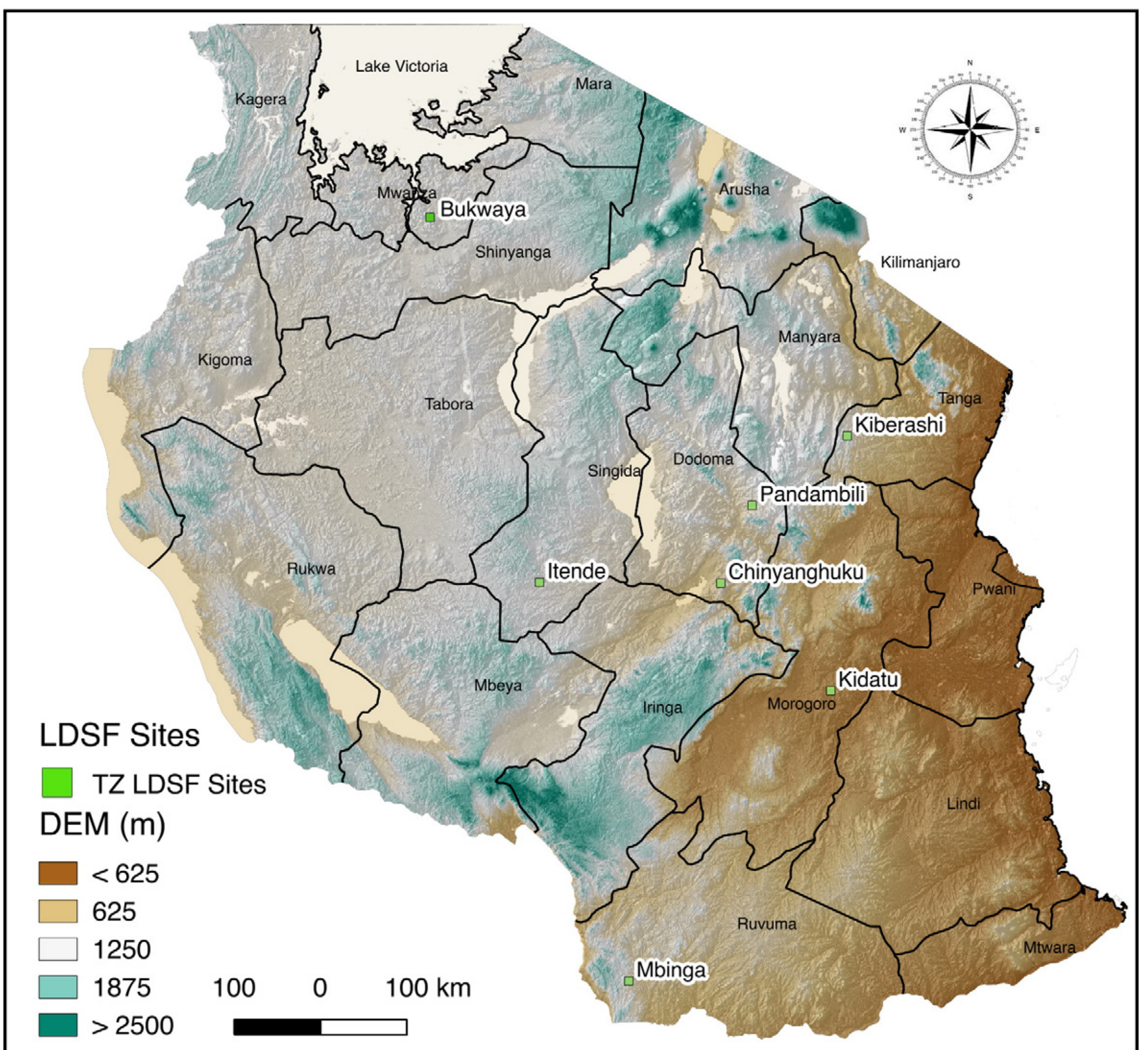

Fig. 1. Location of the seven LDSF sites in Tanzania used in this study overlaid on a digital elevation model.