

Land Health Surveillance: Mapping Soil Carbon in Kenyan Rangelands

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Abstract Land health surveillance is a methodological framework for measuring and monitoring land health—the capacity of land to sustain delivery of ecosystem services—for the purpose of targeting agroforestry and other sustainable land management in landscapes, and assessing their impacts. It is modelled on scientific principles used in surveillance in the public health sector, which has a long history of evidence-informed policy and practice. Key elements of the science methodological framework are (1) probability-based sampling of well-defined populations of sample units; (2) standardized protocols for data collection to enable statistical analysis of patterns, trends, and associations; and (3) multilevel statistical modelling of land health attributes at different scales, including in relation to satellite imagery for spatial interpolation. The framework was applied in assessing soil carbon in Kenyan rangelands in Laikipia. Systematic probability-based field sampling provided a robust baseline on condition in the study area. Infrared spectroscopy was used in the laboratory as a rapid low-cost tool for estimating soil carbon concentration. The georeferenced soil carbon values were modelled to reflectance values of fine resolution (2 m) satellite imagery and spatially interpolated over the 100-km² sampling block. The combination of methods makes soil carbon baselines feasible at a landscape level in land management projects and provides much additional information on soil and vegetation health for targeting interventions. The land health surveillance approach could form the basis for evidence-based decision making on land management at project, national, and even continental levels.

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Introduction

There is increasing recognition of the importance of safeguarding land health—the capacity of land to sustain delivery of essential ecosystem services—for global development and environment (MA 2005). Despite much attention paid to land degradation indicators and assessments (e.g. Vogt et al. 2011; Winslow et al. 2011), there is still a lack of scientifically sound approaches for defining, measuring, and monitoring land health at different scales. Basic problems include lack of proper sampling frames that permit inference to the population level from well-defined sample units (Cochran 1977) and lack of consistent measurement methods that can be applied across diverse landscapes so that results can be compared in wider spatial and temporal contexts. There is little hope for making progress on assessing land degradation until proper baselines and monitoring systems are put in place. Land health surveillance, developed by the World Agroforestry Centre, is an approach designed to overcome these limitations and is modelled on scientific approaches that have been used for decades in public health monitoring (Box 1).

Land health surveillance aims to provide high-quality spatial data on land health problems and risks to (1) help target sustainable land management interventions and (2) provide a baseline and method for monitoring changes in land health over time to be able to assess trends and impacts of interventions. The approach combines (1) consistent, georeferenced field measurements of vegetation and soil conditions and soil sampling, (2) use of new light-based (spectral) techniques for analyzing large numbers of soil samples at low cost, (3) use of remote sensing data to provide land health metrics at national to regional scales, and (4) scientific

Box 1: Surveillance Science Principles

- Case definitions are used to specifically and consistently diagnose health problems.
- Standardized screening tests are used to consistently assign individual samples to cases.
- Sampling designs are used to make inferences about the health of target populations.
- Sample units that make up the population are unambiguously defined.
- The frequency of health problems in populations (prevalence/incidence) is assessed.
- Association between health indicators and risk factors is assessed using statistical (risk quantification) models.

Source: Shepherd and Walsh (2007)

workflows that combine field, laboratory, and remote sensing data in statistical models to provide digital maps and quantitative information designed to support specific decision problems.

The Land Degradation Surveillance Framework (LDSF) is the basic field sampling methodology being applied in the Africa Soil Information Service which is sampling 60 randomized sentinel sites (10×10 km sampling sites) throughout sub-Saharan Africa (Fig. 1). This is the first ever attempt at taking a ground-based, unbiased, population-level sample of African land condition. For example, these data enable quantitative analysis of the relationships between woody cover and distribution and soil health (Fig. 1).

In this chapter, we illustrate some results of applying the LDSF methods in a rangeland management project in Laikipia, northern Kenya. The field measurements were conducted by a small private conservation company, Wajibu MS, in partnership with local communities, as part of a holistic rangeland management project in North Laikipia. A key feature of holistic management is the use of livestock to improve degraded and denuded lands, for example, by planned grazing to allow recovery periods for grass growth, rotation of bomas for manure management, and removal of unwanted invasive plant species. The land health surveillance methods were deployed to provide a baseline and monitoring framework for measuring impacts on land health at a landscape scale. The focus of this chapter is mapping soil carbon, as this is a key soil quality indicator.

Study Area

Field sampling was conducted in two LDSF sites encompassing 10,000 ha each within a 40,000 ha area, centred on the Sanctuary at Ol Lentille. One site was in the south (Ol Lentille) and one in the north (Kipsing) of the project area (Fig. 2). The project site is located 75 km northwest of Nanyuki in north central Kenya, transcending the borders of North Laikipia and Isiolo Districts, in the Mukogodo Division of Laikipia District, and Oldonyiro Division of Isiolo District. The study area falls under semiarid to arid agroecological zones and is a part of the Upper Ewaso Ng'iro North River Basin. The southern part is characterized by vertiginous highlands and rolling plateaus with an altitude of 1,600–1,800 m, while the northern section sits on an alluvial flood plain with altitudes of 1,100–1,250 m. Rainfall distribution is bimodal with peaks of “long rains” mid-March to mid-June and “short rains” mid-October to mid-December. Six broad vegetation types can be characterized: dense woodland, open woodland, sparsely shrubbed woodland, open shrubbed grassland, open grassland, and closed grassland. Woody species in the study area predominantly belong to the Mimosoideae family, while *Eragrostea*, *Chloridea*, and *Stipeae* families are the most dominant Gramineae. Historically, the area was used for dry-season grazing by nomadic pastoralists, but in recent years, burgeoning population and government development policies have led to increasing permanent settlements in the area.

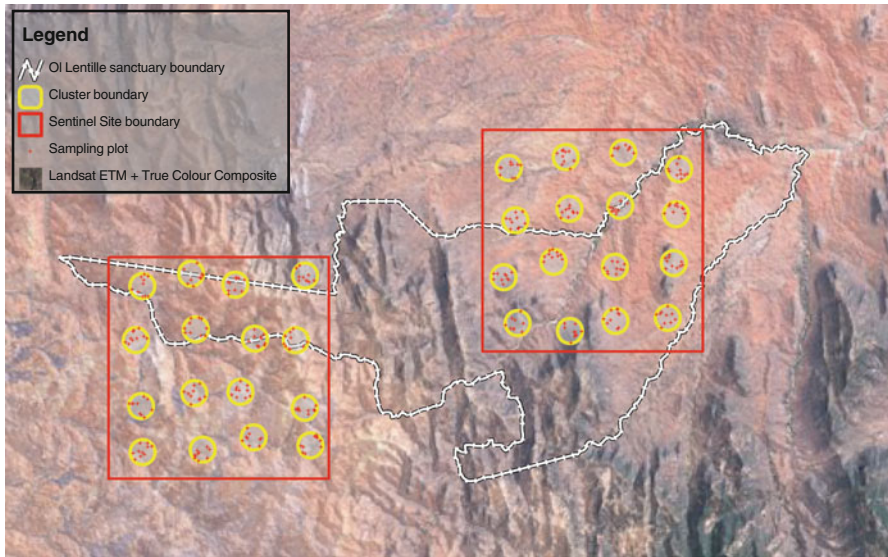


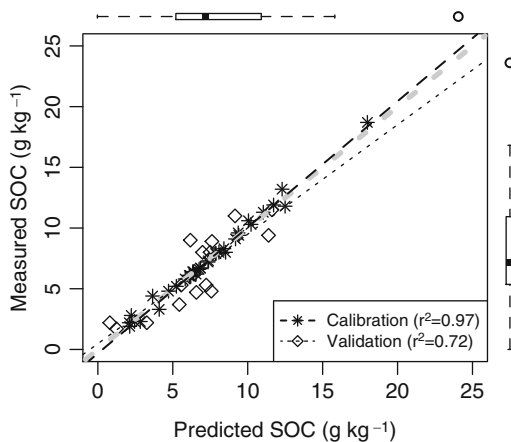
Fig. 2 Overview of the Sanctuary at OI Lentille and the two LDSF (Land Degradation Surveillance Framework) sites in Laikipia, Kenya, included in this study

of ten plots, with randomized centre-point locations falling within a 564-m radius from each cluster centroid (Fig. 2). Thus, sentinel sites have two (or in some cases three) levels of randomization, which minimizes local biases that may arise from convenience sampling. Each plot has an area of 1,000 m² and consists of four subplots of 100 m² each. The coordinates of the plots are loaded onto a GPS (Geographic Positioning System), which is then used to navigate to each point.

Georeferencing and infiltration measurements are completed in the centre of the plot, and soil samples are composited to the plot level from the subplots for topsoil (0–20 cm) and subsoil (20–50 cm) depths. Soil samples are recovered using a soil auger and soil mass of samples recorded to allow calculation of soil carbon stocks on a soil volume basis. Soil depth to restrictions is recorded. A range of observations and measurements are made at the plot level to provide comprehensive information on ecosystem condition. These measurements have been designed and tested to be feasible under the difficult conditions in rural Africa. Further details of the protocol are given in Vågen et al. (2010a, b). A sentinel site can be completed by a small field team (five people) within 12–16 days, depending on the terrain and accessibility.

Soil infrared spectroscopy (Shepherd and Walsh 2007) is used as the main soil analytical tool due to its low-cost and high-throughput capability. Conventional soil testing methods are performed on 10–20 % subset of samples and calibrated to the infrared spectra, typically using partial least squares regression or multilevel regression models. For high-resolution mapping of soil organic carbon (SOC), QuickBird imagery was used and models developed based on Minimum Noise Fraction (Green et al. 1988) transposed image reflectance values, which were related to measured SOC

Fig. 3 Measured SOC, soil organic carbon ($\log \text{ g kg}^{-1}$), using combustion against values predicted from near-infrared spectroscopy for calibration and validation data sets



values, allowing for prediction of SOC concentrations in the study area. The result is a wall-to-wall carbon map. Analytical methods are described in Vågen et al. (2010b) and Aynekulu et al. (2011).

Results and Discussion

The calibration of soil organic carbon concentration to near-infrared diffuse reflectance spectra was robust, as evidenced by the prediction performance of a hold-out validation set (Fig. 3). Predictions of SOC concentrations in the study area based on QuickBird MNF components are also robust, relative to near-infrared (NIR)-predicted values (Fig. 4) with an adjusted R² of 0.82. In Fig. 5, the resulting map of SOC concentrations for the Sanctuary at Ol Lentille and surrounding areas is shown. Low carbon values are observed along the sandy river courses, and high values in hilly areas with higher tree densities. On average, Ol Lentille has about 3 g SOC kg⁻¹ higher concentrations than Kipsing.

The soil carbon information can be combined with other information on soil physical degradation risk, soil fertility status, topographic data, and vegetation characteristics to assist in targeting agroforestry and sustainable land management interventions. For example, areas that have low soil organic carbon levels (relative to areas under good vegetation cover and similar soil texture) but low prevalence of other constraints may be prioritized for kraaling to increase manure inputs and increase grass productivity. Areas with low soil carbon saturation in areas with otherwise good soil fertility potential may be targeted for conservation agriculture practices incorporating trees. Areas with inherent soil physical constraints such as restricted soil depth and low infiltration capacity, but with currently low tree cover, can be flagged as environmentally sensitive or marginal areas to which afforestation efforts may be directed.

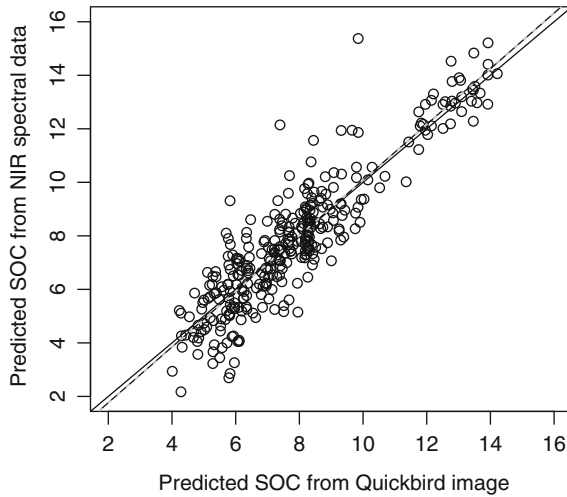


Fig. 4 Soil NIR-predicted values of SOC versus QuickBird Minimum Noise Fraction-predicted soil organic carbon for the study area in Laikipia, northern Kenya

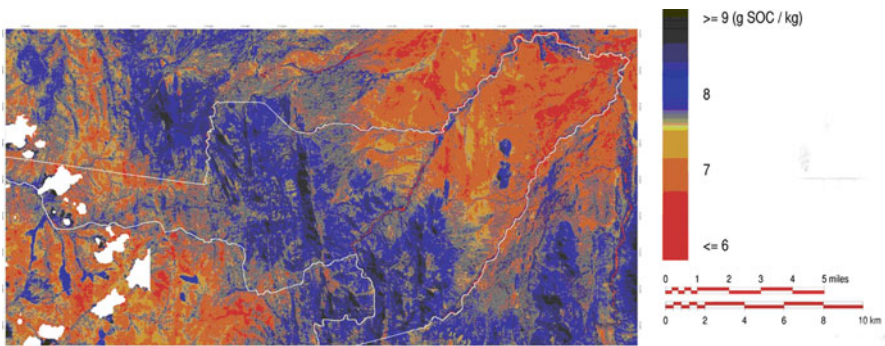


Fig. 5 Map of topsoil SOC (g kg^{-1}) for the Sanctuary at Ol Lentille and surrounding areas, Kenya

Conclusion

Combining systematic ground measurements and soil sampling with high-throughput soil analytical methods based on infrared spectroscopy and remote sensing imagery, linked up using multivariate multilevel statistical modelling, has potential to enable land and soil health monitoring in landscapes. Routine use of these tools at different scales can help land users and governments make better, evidence-informed decisions on land management as part of everyday policy and practice. Further work is needed to combine the various indicators of land and soil health into a framework for providing specific land management recommendations.

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References

- Aynekulu E, Vågen T-G, Shepherd KD, Winowiecki L (2011) A protocol for measurement and monitoring soil carbon stocks in agricultural landscapes. Version 1.1. World Agroforestry Centre, Nairobi
- Cochran WG (1977) Sampling techniques, 3rd edn. Wiley, New York
- Green AA, Berman M, Craig MD, Switzer P (1988) A transformation for ordering multispectral data in terms of image quality with implications for noise removal. *IEEE Trans Geosci Remote Sens* 26:65–74
- MA (2005) Ecosystems and human well-being, vol. 1: Current state and trends, Millennium ecosystem assessment. World Resources Institute/Island Press, Washington, DC
- Shepherd KD, Walsh MG (2007) Infrared spectroscopy—enabling an evidence-based diagnostic surveillance approach to agricultural and environmental management in developing countries. *J Near Infrared Spectrosc* 15:1–19
- Vågen T-G, Shepherd KD, Walsh MG, Winowiecki L, Desta LT, Tondoh JE (2010a) AfSIS technical specifications: soil health surveillance. Version 1.0. Africa Soil Information Service, Nairobi
- Vågen T-G, Winowiecki L, Desta LT, Tondoh JE (2010b) The Land Degradation Surveillance Framework (LDSF) field guide. Africa Soil Information Service, Nairobi
- Vogt JV, Safriel U, Von Maltitz G, Sokona Y, Zougmore R, Bastin G, Hill J (2011) Monitoring and assessment of land degradation and desertification: towards new conceptual and integrated approaches. *Land Degrad Dev* 22:150–165
- Winslow MD, Vogt JV, Thomas RJ, Sommer S, Martius C, Akhtar-Schuster M (2011) Science for improving the monitoring and assessment of dryland degradation. *Land Degrad Dev* 22:145–149