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Spatial assessments of soil organic carbon for stakeholder decision-making. A case study from Kenya

Abstract

Land degradation impacts the health and livelihoods of about 1.5 billion people worldwide. Given that the state of the environment and food security are strongly interlinked in tropical landscapes, the increasing need for land for food production, urbanization and other uses pose several threats to sustainability in the long term. There is increasing recognition that more integrated approaches to assessments and management of ecosystem health are needed to meet the targets of the 2030 Agenda, including SDG 15.3. In addition to systematic and reliable biophysical and socio-economic assessments, stakeholder engagement with evidence is crucial to support integrated approaches. This paper demonstrates the integration of land and soil health maps with socioeconomic datasets into an online, open-access platform called the Resilience Diagnostic and Decision Support Tool for Turkana County in Kenya, using the Stakeholder Approach to Risk Informed and Evidence Based Decision Making (SHARED) methodology. The paper highlights the utility of spatial assessments of soil organic carbon (SOC) for monitoring of land degradation neutrality (LDN) compliance, understanding the drivers of SOC dynamics, and inclusion in stakeholder decision-making. The main objectives of this paper were to: 1) demonstrate the application of a systematic approach for land health assessments, including spatial mapping of soil organic carbon; 2) show an operational interdisciplinary framework for assessing ecosystem health; and 3) showcase the application of evidence-based tools for stakeholder engagement using the SHARED approach.

Keywords: soil organic carbon, stakeholder engagement, remote sensing, evidence-based decision making, resilience

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1. Introduction

The 2030 Agenda, including multi-lateral environmental agreements and the Sustainable Development Goals (SDGs), has set the stage for greater appreciation and understanding of the complex nature and interactions among environmental challenges facing society. SDG 15 calls for the protection, restoration and promotion of sustainable use of terrestrial ecosystems, sustainably managed forests, combating desertification, halting and reversing land degradation and halting biodiversity loss.

At their core, initiatives such as Land Degradation Neutrality (LDN) and SDG 15 emphasize healthy ecosystem function and resilient landscapes, which underpin healthy economies and societal well-being. Because these issues are intrinsically inter-related, decisions around soil and land cannot be taken in isolation. Achieving the associated targets, requires a robust evidence base for measuring and monitoring land health indices and associated land management practices, coupled with local and policy level awareness of the importance of land health in supporting multiple sectors. Also, local capacity to implement, monitor and assess these indicators is needed, including mechanisms for integrated, cross-sectoral coordination and inclusive, multi-stakeholder collaboration to achieve impact.

Many assessments of land health suffer from (i) disagreements about the definition of land degradation/ land health; (ii) an abundance of indicators that are often not feasible to measure and hence operationalize, and (iii) a lack of rigorous science-based analytical frameworks. Comparable indicators are critical when assessing environmental conditions and progress made towards the mitigation or avoidance of land degradation, but they are also important to effectively communicate information both to stakeholders such as farmers or advisory services, and to policy makers. In addition to being comparable, indicators for assessment and monitoring of land health should be a) science based; b) readily measurable (quantifiable); c) rapid; d) based on field assessment across multiple scales (plot, field, landscape, region) and e) representative of the complex processes of land degradation in landscapes. The methods, tools and approaches presented in this paper offer realistic and cost-effective options both for baseline assessments of LDN indicators and for monitoring of progress towards LDN targets. Specifically, the three LDN indicators include: 1. Trends in land use/cover; 2a. Trends in land productivity; and 2b. Trends in soil organic carbon stocks (UNCCD, 2015). Several assessments of methodologies for LDN compliance (Aynekulu et al., 2017; Caspari et al., 2015; Stavi and Lal, 2015) also highlight the need for consistent, spatially explicit data over time.

The Land Degradation Surveillance Framework (LDSF) is an example of a method that has been applied in a number of projects in the global tropics to provide more rigorous, science-based, assessments of land degradation risk and status, as well as soil health (Vågen et al., 2013a). An important indicator of soil health is soil organic carbon (SOC), and field datasets collected using the LDSF have been used to provide spatially explicit assessments of SOC and other indicators of land degradation processes such as soil erosion, in addition to other soil functional properties (Vågen et al., 2012, 2016; Winowiecki et al., 2016a, 2016b). These assessments can be used to inform spatially explicit land and soil health monitoring systems, which are critical in order for countries to avoid land degradation, or to restore already degraded ecosystems. Combining systematic data collection efforts with rigorous analytical frameworks, evidence-based approaches can be used to engage stakeholders with interactive online user-friendly platforms to inform national and international policy makers.

Within this context, the engagement of stakeholders becomes an important element to prioritize investment strategies for accelerating the achievement of the SDGs. The Stakeholder Approach to Risk-informed and Evidence-based Decision-making

(SHARED)1 emerged in response to this need and was developed around a number of key factors, steps and principles, including: i) advancing a holistic or systems view to raise awareness on the integrated nature of environmental, social, cultural and economic dimensions and causal relationships; ii) establishing a clear understanding of the influencing factors of human and group decision making including stakeholder analysis; iii) facilitating different government sectors and multi-stakeholder platforms of diverse societal sectors; iv) collectively articulating mutually agreed, desired sustainable development outcomes and indicators building upon fundamental ecosystem services and nested within national and global goals, v) generating evidence and experience and tailoring tools in a readily consumable way for problem solving and options identification, vi) testing options based on collectively defined criteria, including risks and potential synergies and vii) designing option implementation with monitoring and evaluation and co-learning feedback into the process.

This paper demonstrates the integration of land and soil health maps, using spatial assessments of SOC as an example, with socio-economic datasets into an online tool, the Resilience Diagnostic and Decision Support Tool2) (RDDST) in Turkana County, Kenya. The main objectives of the efforts discussed in this paper were to: 1) demonstrate the application of a systematic approach for land health assessments, including spatial mapping of soil organic carbon; 2) demonstrate the operationalization of interdisciplinary framework for assessing ecosystem health; and 3) showcase the application of evidence-based tools for stakeholder engagement using the SHARED approach. The approaches presented can also be applied as part of LDN efforts to assist countries in more effectively restoring degraded lands and increasing agricultural productivity, including opportunities for sustainable development and biodiversity conservation (IUCN, 2015). A recent assessment of land degradation in Kenya estimates that the annual cost of land degradation is at approximately 1.5 billion USD, which represents about 5% of the country's GDP (Munoz, 2016). Kenya has endorsed the SDG 15.3 targets and discussions on baseline assessments and monitoring are underway. Given the large extent of drylands in Kenya, their management will be critical to achieving these targets.

2. Methodology

This paper utilizes spatial assessments of SOC that were conducted using data from a network of Land Degradation Surveillance Framework (LDSF) sites in the global tropics. The LDSF was designed for practical and cost-effective soil and ecosystem health surveillance, including for mapping of SOC (Vågen et al., 2013a, 2016; Winowiecki et al., 2016a, 2016b). The framework is also designed to monitor changes over time, and provides opportunities for targeting improved soil management and land restoration activities (Lohbeck et al., 2017). Specifically, the LDSF systematically assesses several

1 http://www.worldagroforestry.org/shared

2 http://landscapeportal.org:3838/sharedApp

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ecological metrics simultaneously at four different spatial scales (100 m^2, 1000 m^2, 1 km^2 and 100 km^2), using a spatially stratified, hierarchical sampling design (Vågen et al., 2013b). The LDSF also applies the latest soil infrared (IR) spectroscopy technologies in analysis of SOC and other soil properties, which are cost effective and hence allow for the scaling of soil measurements. The spatial assessments of SOC included in this study were developed based on an archive of 10,000 georeferenced LDSF plots with soil samples that were analyzed for SOC and mid-infrared analysis at the ICRAF Soil and Plant Diagnostics Lab in Nairobi, Kenya and used to conduct spatial predictions of SOC concentrations and stocks using reflectance data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor (Vågen et al., 2016). The spatial assessments of SOC published in Vågen et al. (2016) were clipped for Turkana County and applied as part of the interactive tools described below. In brief, the accuracy of the spatial estimates of SOC based on MODIS as measured using the root-mean squared error of prediction (RMSEP) for three independent model test runs ranged from 9.6 to 11.5 g C kg^{-1}.

An interactive dashboard was developed for Turkana County using the Shiny web framework for R statistics (Chang et al., 2017), integrating existing and new data and providing data management and graphical tools to allow users to interact with these data in a meaningful way. The RDDST dashboard is hosted on the ICRAF Landscape Portal[3], which provides various tools for spatial data storage and visualization. Through robust data management and advanced data visualization, the RDDST was co-developed with stakeholders in Turkana County to help facilitate communication of data and analysis between scientists and stakeholders. This allows for the interrogation of evidence, an increased rate of discovery and helps contextualize the data used. Data sources for the RDDST included the Armed Conflict Location & Event Data Project (ACLED) for security data, Kenya government statistics for education and health data, and data from the Hunger Safety Net Programme (HSNP) for information on livestock populations and energy use within the county.

The SHARED approach was applied to foster the innovation required to shape and embed land health assessments into inclusive negotiation and decision-making processes. SHARED is a comprehensive framework tailored to specific decision needs; it brings together processes, evidence and tools to shift the decision paradigm towards more inclusive, inter-sectoral and inter-institutional integration to tackle complex decisions and achieve desired outcomes. This targeted facilitation ensures cohesive communication across multiple institutions, political levels and knowledge systems to develop capacity and the evidence-base as a continuously linked process, within the same development outcome pathway. At the national level, the SHARED approach has been used in collaboration with Kenya's Ministry of Environment and Natural Resources and the Ministry of Agriculture, Livestock and Fisheries to synthesise the evidence of 44 integrated crop-livestock-tree system projects to develop recommendations for climate-resilient approaches (Chesterman and Neely, 2015) and to directly inform the drafting of Kenya's National Climate Change Policy Framework (Neely, 2014). In Turkana County, this process was carried out through four stages: (i) Establishment of the context of data and information use at county level, (ii) data scoping, cleaning

3 http://landscapeportal.org/sharedApp

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and synthesis, (iii) co-development of data visualizations and capacity for data interpretation and use, and (iv) targeted capacity building to embed the data management systems and tools into county functions. The latter process is ongoing and focuses on capacity building of key county staff on protocols and methods to collect, enter and update data, which are critical components to ensure the sustainability of the frameworks introduced.

3. Results

Soil organic carbon (SOC) concentrations were mapped for Africa at 500m spatial resolution (Vågen et al., 2016) and clipped for Kenya (Figure 1) for use in stakeholder engagement processes within Turkana County (see county outlined in Figure 1). Given the emphasis on management of SOC as a critical resource for both agriculture and rangeland management in Turkana County, SOC concentrations were applied in the RDDST rather than estimates of SOC stocks.

[Figure 1 here]

A map showing concentrations of SOC for Kenya is shown in Figure 1, while the distribution of estimated SOC in topsoil is presented in Figure 2, based on estimates published in Vågen et al. (2016). The distribution of SOC for Turkana County is also included in Figure 2, showing the very low SOC concentrations in the county in general, which is consistent with the low SOC concentrations generally found in the drylands of the northern and north-eastern parts of the country (Figure 1). However, it is worth noting that SOC is relatively heterogeneous within these areas and that there are pockets of high SOC in parts of the drylands such as the Matthews Range and mountains such as Ndoto, Marsabit and Kulal, as well as Loima Hills in Turkana County. These areas represent critical SOC pools, are important resources for pastoralists in the drylands for dry-season grazing (Oba et al., 2000), and are hotspots for biodiversity in the region.

[Figure 2 here]

In Turkana County, maps of SOC concentrations were adapted from Vågen et al. (2016) and integrated into the RDDST tool as a key indicator of land health and ecological resilience within the county. The RDDST was developed to support cross-sectoral decision-making processes (Figure 3), integrating data from across numerous sectors, including security, education, livestock, energy, human health and land health.

Through a series of workshops facilitated using the SHARED process, the RDDST was co-developed with representatives from the Turkana County government and other stakeholders such as representatives from UN organizations and Non-Governmental Organizations (NGOs) operating within the county.

The land health module of the RDDST was used to interactively visualize and explore SOC (Figure 5) as a key indicator of land health across the county, In addition, a module for exploring vegetation cover status and trends was applied for assessing vegetation performance and trends. The module was developed with three effective layers of detail, with the first page detailing

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hotspots of erosion, targeted at policy makers, and the two following pages of the module dedicated to more detailed representations targeted at planning and natural resource officers within relevant ministries.

Participants learned that SOC is an important and measurable indicator of soil health and that it regulates several ecosystem functions that are critical for supporting productive agricultural and pastoral landscapes of the county. Using the interactive SOC maps and other parameters of land health, decision makers could readily view areas that were degrading and for which restoration investments would be most feasible. A key aspect of the co-design process was to ensure clear definition of SOC and how this related to other indicators of importance within the county, for example reflecting how changes in SOC could impact on grazing potential of the land, with pastoralism the predominant livelihood within Turkana County. Feedback from the representatives of the County Ministries highlighted their understanding of the value of SOC, its role in ensuring landscape health in the semi-arid region and the importance of taking SOC into account in investment decisions.

These tools are being used to demonstrate the critical role of the underpinning natural resource base and the importance of taking this into account in decision making across multiple sectors. Furthermore, the outcomes of these workshops and the RDDST was imbedded as a key tool within the Department of Planning, with its open source parameters, added to the county website and applied in the development of the Turkana County Integrated Development Plan for the period 2018 to 2022. Visualization of local land health parameters in conjunction with data from other sectors shifted the discourse in the County Government and resulted in the identification of integrated flagship projects (linked budgets across multiple ministries) for inter-sectoral working activities, with joint investment in and health restoration to assist multiple development outcomes. Appendix One details the outcomes of the engagement process and the various modules of the RDDST.

[Figure 3 here]

[Figure 4 here]

4. Discussion

Consistently developed indicator frameworks such as the LDSF, combined with systematic field and lab measurement protocols, allow for spatial assessments of SOC and other land health indicators at multiple spatial scales and with unprecedented accuracy and spatial coverage. Such spatial assessments can be applied at continental and regional scales (Vågen et al., 2016), as well as at country and local scales (Figure 1 and Figure 2), with results integrated directly into decision making processes at local level, as demonstrated for Turkana County (Figure 3 and Figure 4). In Kenyan drylands, which make up more than 80% of the area of the country and where the primary land use is livestock production, SOC concentrations and stocks are low due to a combination of climatic conditions and widespread land degradation. Spatial estimates of SOC stocks for Kenya reported in Minasny et al. (2017), show the lowest estimated C stocks in arid and semi-arid regions of the country

(<20 $Mg\ C\ ha^{-1}$ on average), such as Turkana County. These estimates are consistent with those reported by Batjes and Batjes (2004) and Vågen and Winowiecki (2013) for arid- and semiarid parts of the country. Higher SOC stocks are found in sub-humid and humid areas, including the central highlands and western parts of the country, such as around Mt Kenya (>100 $Mg\ C\ ha^{-1}$), the Aberdares, the Mau Forest Complex and Kakamega forest, but also in mountain areas within the drylands. These forest systems, while making up a small proportion of the country's area, are critical carbon pools and also represent important water towers that millions of Kenyans rely on for their water supply (Mogaka et al., 2005). Also, wetland ecosystems such as inland riverine and palustrine areas are critical SOC pools in Kenya and in much of East Africa. In the drylands, such wetland systems are particularly critical for SOC storage and land health, frequently reaching between 80 and 100 $Mg\ C\ ha^{-1}$ at 0 to 30cm depth. The management of these wetland systems is of critical importance for SOC storage and overall land health. Other wetland systems, many of them under threat, such as around the Rift Valley lakes and lacustrine wetlands along Kenya's coast are also examples of ecosystems that are critical for C storage (Minasny et al., 2017; Saunders et al., 2007) and other ecosystem services (Zedler and Kercher, 2005) in the country.

Land degradation in Kenyan drylands is the result of several factors, including substantial migration into these areas, which has resulted in a large growth in their population starting as early as over 30 years ago (Bernard, 1985) and soils that are alkaline and prone to soil erosion. This, along with other factors, has in turn resulted in overgrazing or inappropriate agricultural practices that have again resulted in accelerated land degradation and loss of SOC. As a result, counties in the drylands of Kenya face serious challenges in terms of restoring degraded lands, including implementing policies and incentives that can help target restoration efforts both in terms of space and context. By applying spatial assessments of land health indicators, SOC being a key indicator in this regard, areas that are degraded can be identified for further assessments of the drivers and processes that are leading to degradation, while at the same time making more realistic assessments of the types of restoration efforts that are likely to be effective given conditions in a certain area or location.

There is great value in using the soil health maps depicting SOC and other attributes for awareness raising and to inform decisions of stakeholders and decision makers, but also as tools for concrete planning of interventions to restore degraded land and increase productivity in rangelands or agricultural areas. Building these data into the RDDST and displaying them in conjunction with data and statistics from other sectors including human health, education, pastoral economies, environment, agriculture, trade, infrastructure and energy among others, supported the facilitation of a new-found attention to the socio-ecological system and associated inter-relationships and an understanding of causal dynamics among the sectors within Turkana County. The Ministry of Economic Planning, working with all of the government sectors and several development actors in Turkana County chose to use the SHARED methodology and the RDDST to guide the new County Integrated Development Plan (CIDP), a 5-year program (2017-2022). Based on the knowledge of the prevalence and location of land degradation in the county, there were multiple county integrated flagships aimed at restoring land health while meeting the priorities of social and economic sectors. Further, the county government chose to cancel an earlier planned infrastructural effort that would have opened up relatively healthy land for degradation. Presenting readily accessible spatial assessments of

SOC and other soil health maps initiated discussion on the fundamental importance of SOC and soil health in general for land restoration to achieving development outcomes and lead to a commitment to bring land health management into integrated planning processes within the county, and to target appropriate interventions to avoid degradation or restore already degraded areas.

5. Conclusions

Recent developments in the use of earth observation data to model and map SOC concentrations and stocks have resulted in the availability of spatial estimates with high accuracy and moderate to fine spatial resolution. Decision support tools increase the utility of spatial assessments of SOC, along with other indicators of soil and land health, by providing users with both interactive dashboards that allow them to map and interact with data and analytical tools for land health diagnostics and targeting of interventions. Through the application of open source platforms and tools, the use of evidence in land health management can also be effectively mainstreamed. In the context of the SHARED approach, this process is enhanced through structured stakeholder engagement, co-learning and co-design of tools. These approaches and tools have the potential to greatly enhance the uptake of management interventions to increase SOC and avoid or reverse land degradation, hence also contributing towards the achievement of LDN and SDG targets.

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Figures

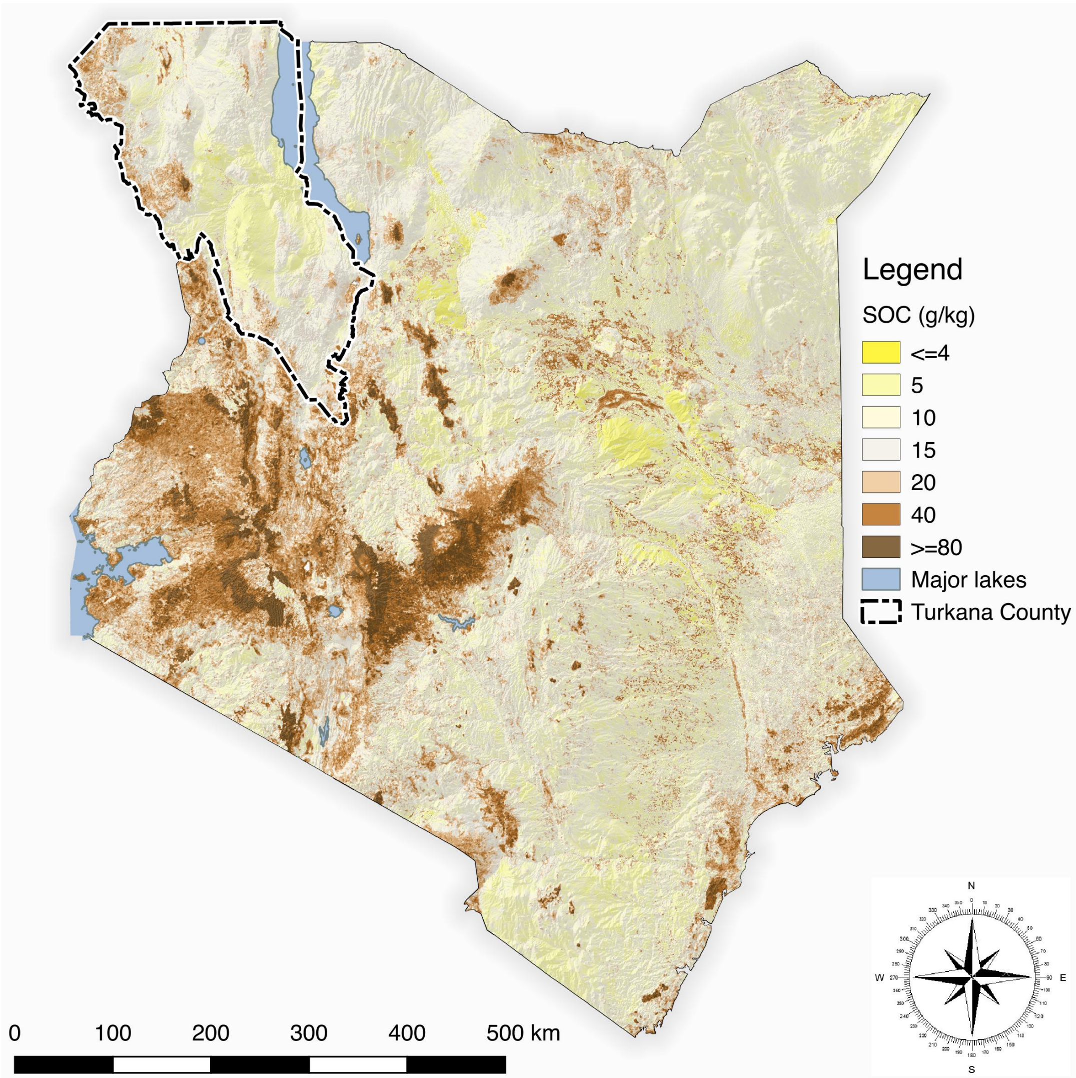

Figure 1. Soil organic carbon (SOC) map of Kenya at 500m resolution (for 2012). Turkana County is located in the north-eastern corner of the country, and is outlined on the map. Adapted from Vågen et al. (2016).

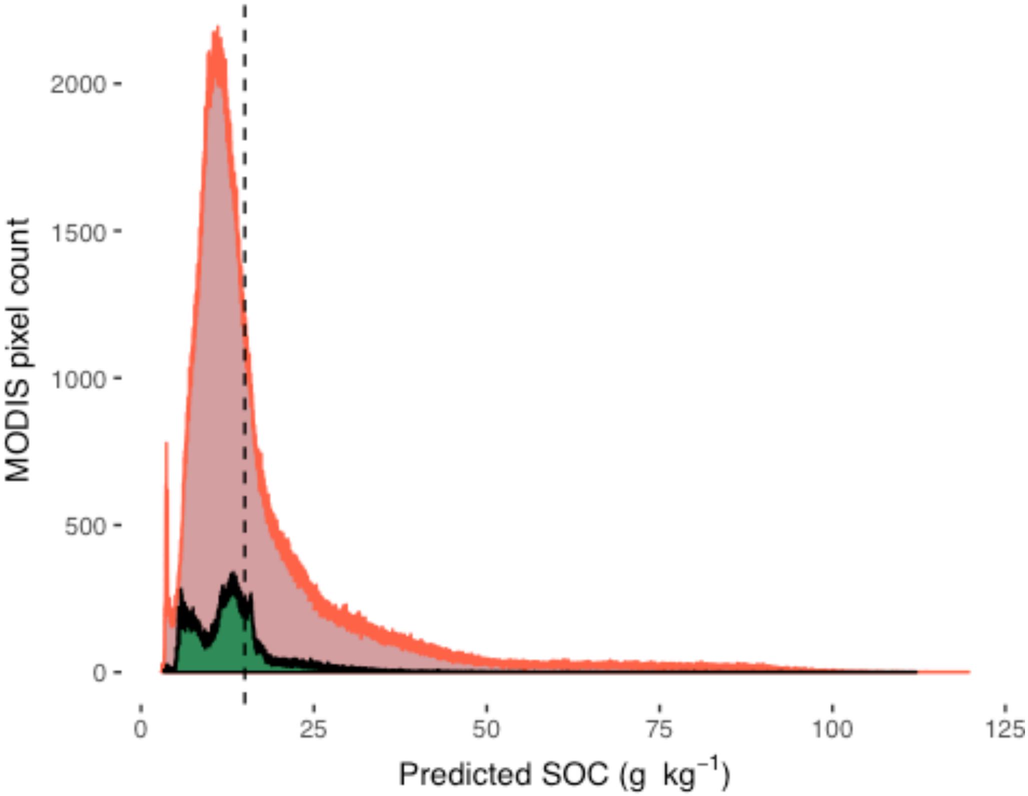

Figure 2. Histograms showing the distribution of SOC in Turkana County (green) versus the rest of Kenya (red). The vertical dashed line represents a SOC concentration of 15 g kg-1

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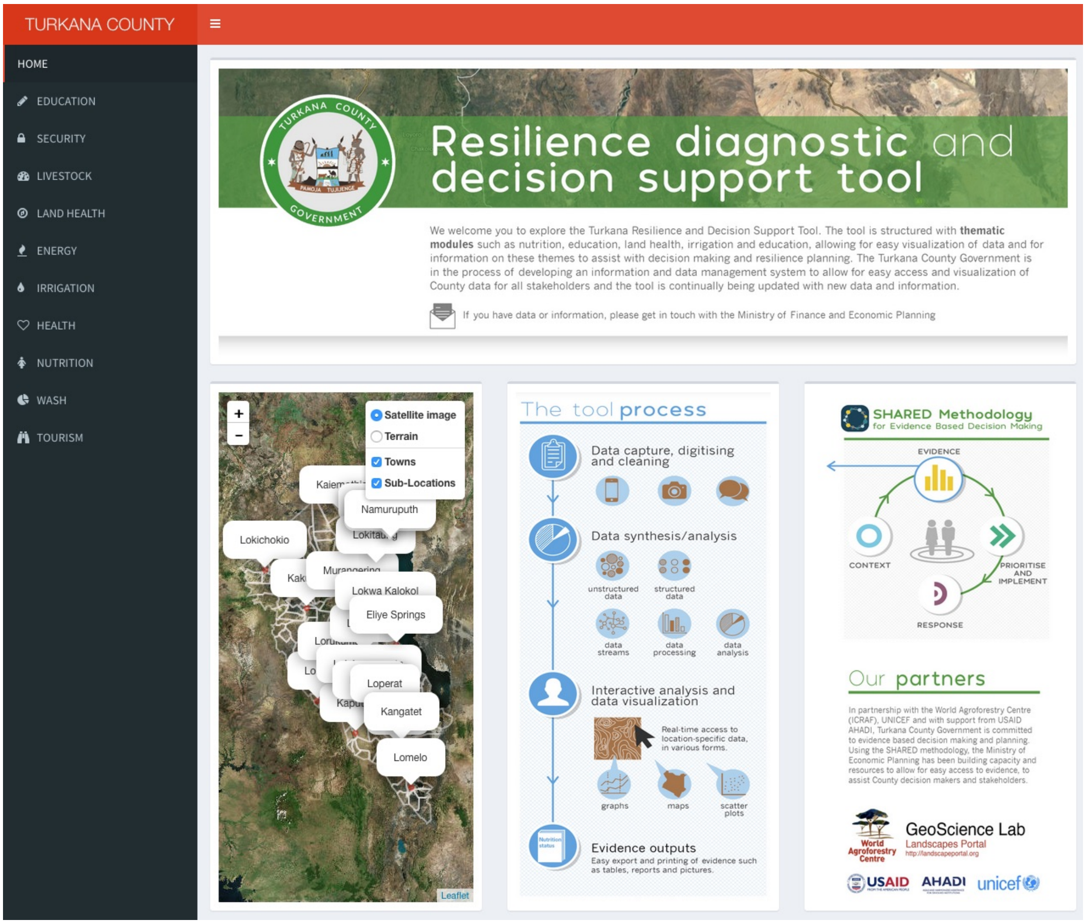

Figure 3. The front page of the Turkana Resilence diagnostic and decision support tool.

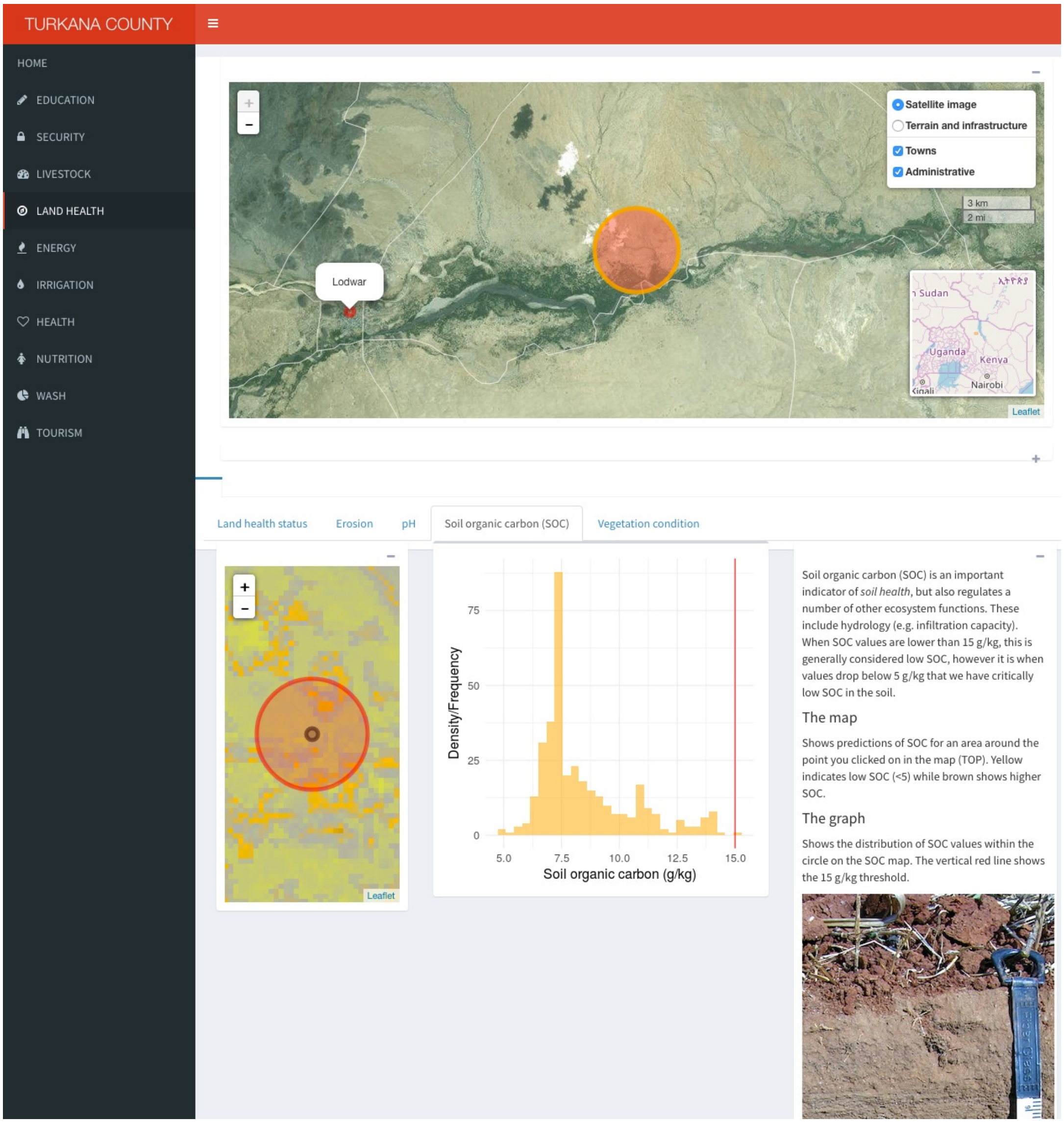

Figure 4. The SOC assessment part of the Turkana Resilence diagnostic and decision support tool, which is part of the land health section of the tool.