Developing Methodology and Capacity for Monitoring Climate Change and its Impacts on Agriculture in Sudan through Earth Observation

Final Project Report

South Kordofan, North Kordofan, White Nile,

Blue Nile, Gezira and Sennar states

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Introduction

Climate change vulnerability is a concept that has been emerging over the last decade and a half, both in climate science and in policy (Füssel and Klein 2006). One of the main aims when conducting climate vulnerability assessments is to reduce *risks* associated with climate change, whether these are related to extreme weather events (e.g. extreme rainfall and flooding), drought, increasing air temperatures, or other issues. There is no single universal definition of climate change vulnerability (Tonmoy, El-Zein, and Hinkel 2014), although the International Panel on Climate Change (IPCC) defines it as:

> Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

An important aspect of the above definition is that vulnerability is strongly related to *resilience*, *marginality*, *susceptibility*, *adaptability*, and *fragility* (Liverman 1990).

According to Tonmoy, El-Zein, and Hinkel (2014), a number of assessments of climate change vulnerability suffer from methodological problems or constraints making it challenging to generalize findings and methodologies. We present analysis that is made accessible through an interactive dashboard, enabling stakeholders in Sudan to conduct spatially explicit indicator assessments that can be overlaid with information from other sources, as outlined above.

Like many other countries in the region, agriculture represents the most important sector of Sudan's economy, contributing to about 35% of the country's GDP or nearly 99% of the country's export earnings if we exclude the oil sector. Approximately 80% of the population is employed in agriculture and related activities. The agricultural sector is very vulnerable to climate change in general and to climate shocks and extreme events in particular, particularly when considering interactions with other stresses such as land degradation and poverty (Zakieldeen 2009). A large proportion of the agricultural sector in Sudan is also rainfed, which means that it is inherently vulnerable to seasonal variations in precipitation (Mohmmed et al. 2018).

Sudan has experienced several dry periods in the past, including in the 1920s, 1950s and between the mid-1960s and mid-1980s (Trilsbach and Hulme 1984), following a pattern observed across the Sahel in general. Studies also suggest that rainfall is becoming increasingly unreliable in Sudan with long-term means across the country decreasing in general between 1990 and 2010, and in particular between 2000 and 2020 (Abduel, Mohamed, Mohamed, Osman, and Zaki 2014). These changes and trends are strongly affecting the agricultural sector given that it mostly relies on rainfed farming. There has also been an expansion of the cultivated area of Sudan over the last 5 decades, although per unit yields of crops are decreasing due to a decline in soil fertility and increased land degradation (Ayoub 1999).

Having timely and spatially explicit information on rainfall events is therefore critical for reducing the vulnerability of agricultural systems in the face of climate change, particularly in marginal agricultural areas. Also, being able to predict extreme events is important for mitigation efforts and for disaster risk management. Sudan established its first weather station as early as 1891 in Sawaken. However, in recent decades, the number of weather stations and rainfall gauges has dropped considerably, resulting in large data gaps. This has resulted in a lack of accurate estimation and prediction of precipitation, and in particular heavy precipitation, which is important for forecasting and managing floods, managing water resources, as well as drought early warning. Hence, earth observation data has become a vital resource for both precipitation and land surface temperature data provision, in addition to land cover and soil property maps.

In the current project, we use an indicator-based approach that assesses biophysical proxies of climate change vulnerability given that it is a complicated phenomenon that is difficult to estimate directly. We conduct spatial assessments of a number of key indicators, including vegetation cover dynamics, soil organic carbon (SOC) and land degradation processes such as soil erosion, in addition to precipitation and temperatures. If we take the example of SOC, this is a useful indicator since it influences multiple aspects of soil health, productivity, and climate change mitigation (Deb, Bhadoria, Mandal, Rakshit, and Singh 2015; T.-G. T.-G. Vågen and Winowiecki 2013), while also playing an important role in determining the adaptive capacity of an ecosystem.

We build assessments of soil and land health on data and predictive models from the Land Degradation Surveillance Framework (LDSF) (T.-G. T.-G. Vågen and Winowiecki 2013; T.-G. Vågen and Winowiecki 2019; T.-G. Vågen, Winowiecki, Abegaz, and Hadgu 2013; Winowiecki, Vågen, and Huising 2016) developed at ICRAF and applied across over 45 countries in the global tropics. By mapping SOC and other soil and land health indicators at high spatial resolution (30m) for the six states included in the project (North Kordofan, South Kordofan, White Nile, Sennar, Gezira and Blue Nile), these indicators can be readily combined with climate data and indicators related to socioeconomic aspects of climate change vulnerability. This is a key step in overcoming one of the main limitations of most current assessments of climate change vulnerability, which are often conducted at relatively high levels of aggregation, such as a state or country level.

Many assessments of land degradation rely on simple indices such as the Normalized Difference Vegetation Index (NDVI). While “greening” or increasing vegetation cover measured using the can mean that land health is recovering, it can also sometimes be associated with for example invasive plant species. Hence, vegetation cover trends need to be interpreted with care and are not enough in themselves to determine whether a system is degrading or recovering. Hence, there is a need for multiple indicators of land health to inform decision-making and for monitoring of change over time.

Objectives of the PCA

The overall objective of the PCA is to enhance the national agricultural monitoring system. This will be achieved through the development of sustainable methods and tools based on the integral use of earth observation and geospatial technology and capacity development. The transfer of skills and good practices and the use of learning materials will help to ensure accurate crop production estimates and integrate the use of remotely sensed data in reporting.

Project activities

The main activities in this project focused on identifying areas that are particularly vulnerable to changes in climate and/or management through the use of a set of biophysical indicators or proxies for indicators that can be readily measured and monitored over time. The project was built on recent advances in hierarchical sampling methods using the Land Degradation Surveillance Framework (LDSF) coupled with earth observation data analytics and novel statistical approaches for assessments and mapping of soil, vegetation, land use and various ecosystem metrics at landscape scale. Building on these advances and the vast libraries of soil, vegetation and remote sensing data collected by and hosted at World Agroforestry (ICRAF), spatial assessments of soil constraints and land degradation were conducted at multiple spatial scales for six states in Sudan.

Baseline mapping at fine spatial resolution (30m) was conducted for;

- Soil condition (soil carbon, pH and other soil functional properties)
- Land degradation risk factors such as soil erosion and root-depth restrictions
- Climate resilience (proxies), such as;
  - Number of days with precipitation
  - Rainfall aggressiveness
  - Mean annual precipitation
  - Annual temperature ranges and trends
- In addition, the following assessments were made where data was available
  - Cropland phenology and biomass/yields
  - Agricultural water use

Finally, an interactive dashboard was developed through a structured stakeholder engagement co-design process using the Stakeholder Approach to Risk-Informed Decision

Making (SHARED) methodology. This dashboard provides stakeholders in Sudan with a user-friendly way of interacting with the various spatial assessments and maps outlined above, providing up-to-date evidence that can be applied at various levels of decision making. In this project, the dashboard was developed for six states in Sudan (North Kordofan, South Kordofan, White Nile, Sennar, Gezira and Blue Nile), however this can be scaled to cover the entire country later through other sources of funding.

Climate and land health data processing and analysis

Identifying and mapping areas that are particularly vulnerable to changes in climate

Daily rainfall data was generated from the Integrated Multi-satellitE Retrievals for GPM (IMERG), based on half-hourly records at 11 km spatial resolution, while monthly and annual land surface temperatures were derived from the MODIS platform (MOD11) at 1 km spatial resolution. A geospatial database was developed to hold both satellite derived datasets and vector data. Spatial data from the above platforms were collated, documented and integrated into a geospatial database for the project states, including the generation of tile-sets for display on the Interactive Sudan Climate Vulnerability Atlas.

Data analytics included spatial and temporal dynamics in rainfall across the six project states, including assessments of extreme events, drought frequencies, seasonal dynamics and floods (see Figure 1). Temporal and spatial dynamics in land surface temperatures were assessed and combined with the rainfall records for the assessment of climate vulnerability, developing a composite climate vulnerability index that was mapped across the six states (Figure 6). Dry days were calculated as the number of days in a year with less than 0.1 mm of rainfall, while extreme temperatures were based on annual median land surface temperatures.

Figure 1: Infographic showing some of the key indicators assessed as part of the analysis of rainfall and land surface temperature earth observation data.

Baseline assessment and mapping of land health

A set of biophysical indicators or proxies for indicators that can be readily measured and monitored over time were assessed and mapped based on the Land Degradation Surveillance Framework (LDSF). The indicators measured as part of LDSF field surveys, a subset of which can be assessed spatially or mapped, is shown in Figure 2. The LDSF was developed as a response to a lack of methods for systematic landscape-level assessment of soil and ecosystem health. The methodology is designed to provide a biophysical baseline at landscape level, and a monitoring and evaluation framework for assessing processes of land degradation and the effectiveness of rehabilitation measures (recovery) over time.

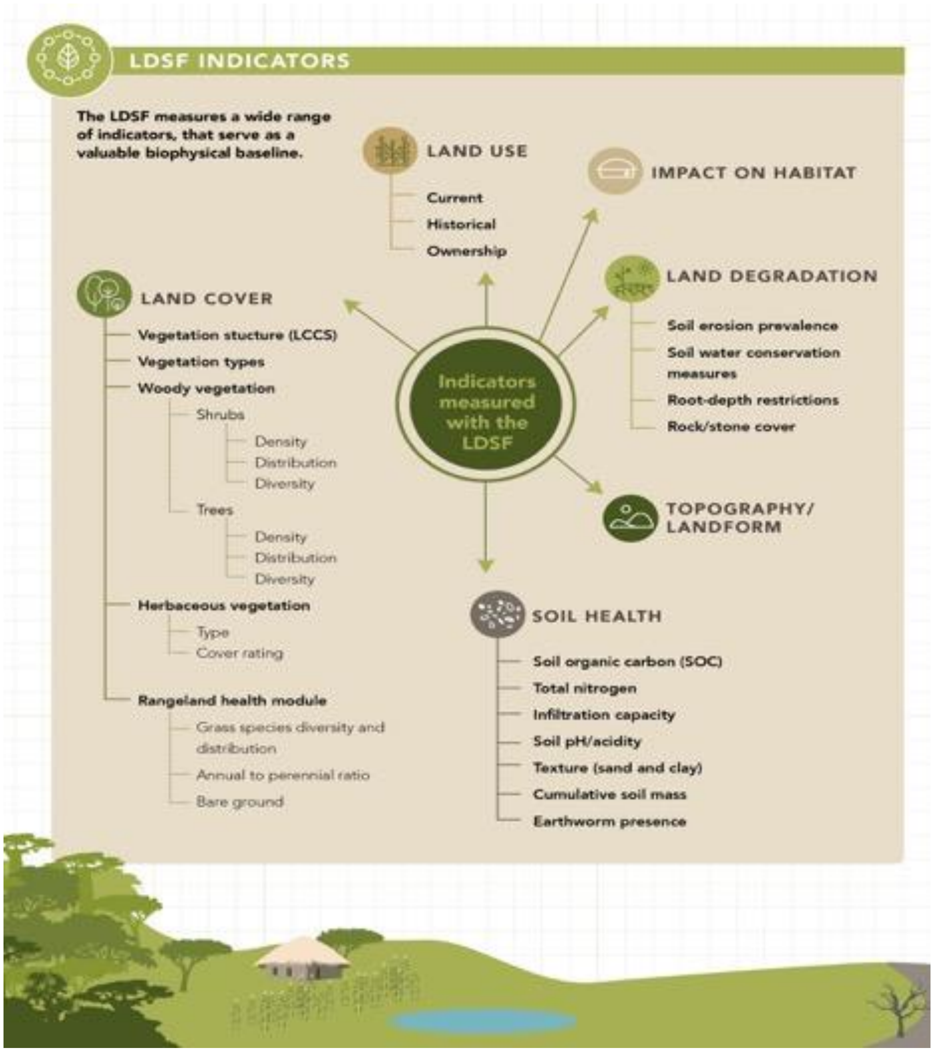

Figure 2: The LDSF indicator framework.

While the LDSF was designed to collect data on biophysical variables across as range of indicators, as summarized in Figure 2. Using the data collected in the field, we apply a range of statistical modeling and machine learning methods to assess land health at multiple spatial scales and across social and ecological systems. Mapping outputs can be produced at multiple spatial scales, with fine-resolution maps produced at 5 to 10 m or higher resolution, high resolution maps at 20 to 30 m and moderate resolution maps at 250 to 500 m resolution. In the current project we used earth observation data from Landsat 8 in conjunction with the LDSF data to produce baseline map at 30 m spatial resolution for the six project states, including soil erosion (Figure 3), SOC (Figure 4), soil pH (Figure 5), other soil properties, and fractional vegetation cover.

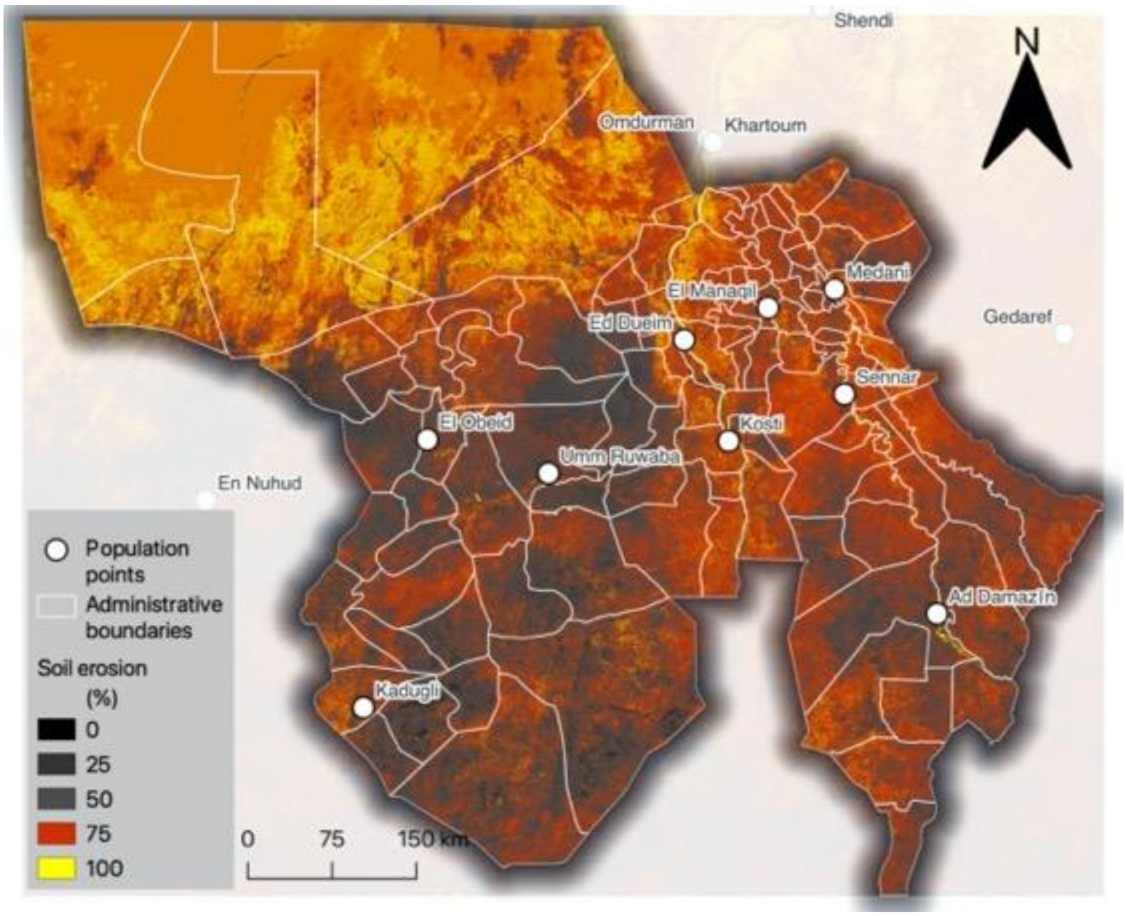

Figure 3: Map of erosion prevalence for the six states included in the project. This map is available in the Interactive Sudan Climate Vulnerability Atlas in an interactive format.

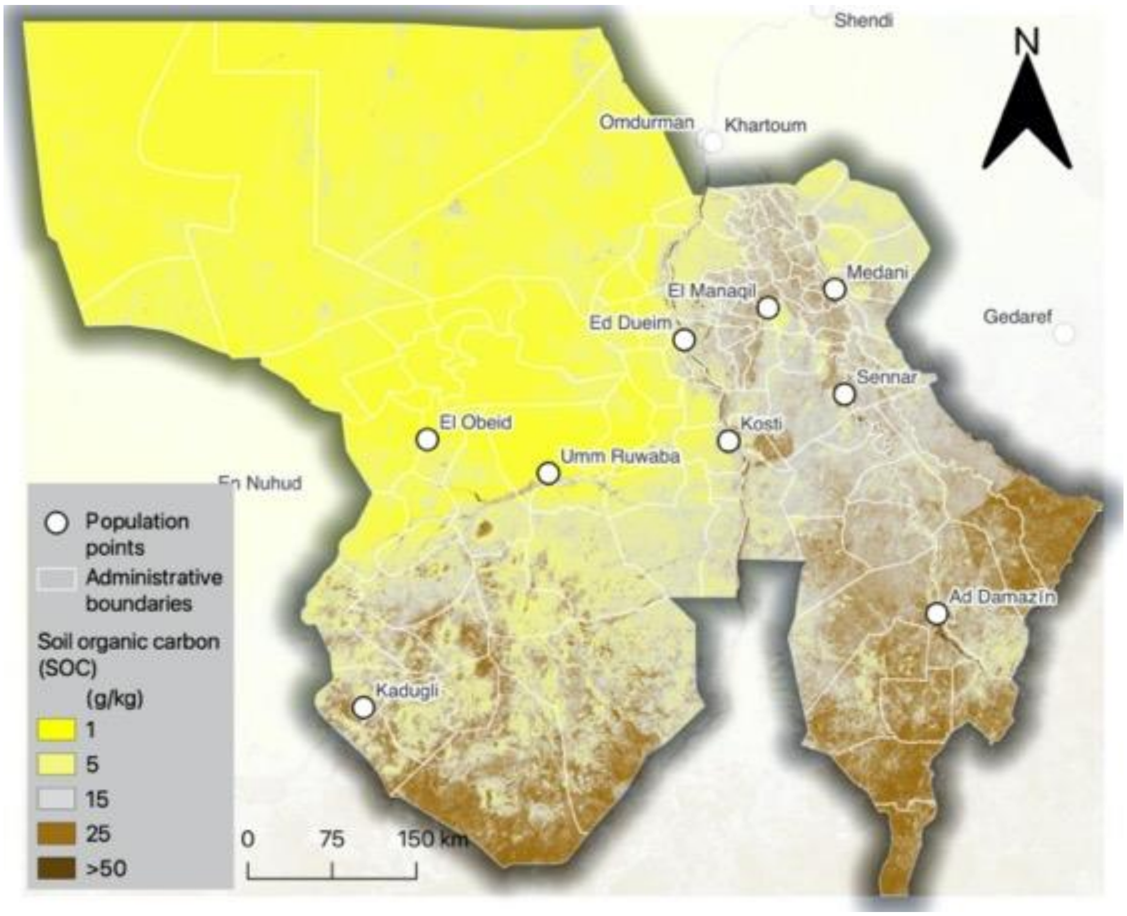

Figure 4: Map of SOC for the six states included in the project. This map is available in the Interactive Sudan Climate Vulnerability Atlas in an interactive format.

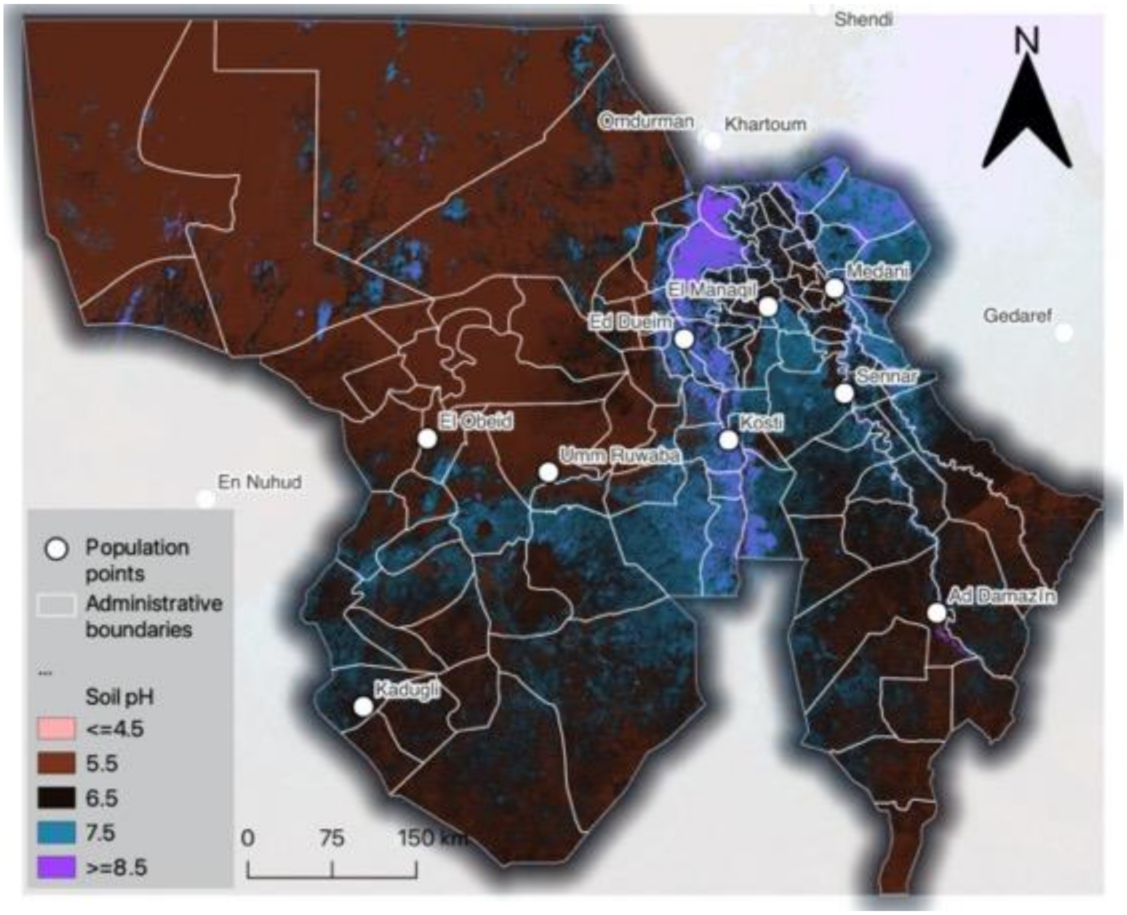

Figure 5: Map of soil pH for the six states included in the project. This map is available in the Interactive Sudan Climate Vulnerability Atlas in an interactive format.

Stakeholder engagement

The project held several engagements with national partners in Sudan, including workshops and regular meetings to ensure an inclusive co-design process and to enhance capacity development. The objectives and outcomes of each engagement are summarized below.

Stakeholder workshop to support the co-design of a Sudan decision dashboard 3-4 November 2020: the co-design workshop brought together participants from various institutions in Sudan including the Ministry of Agriculture, the Higher Council for Environment and Natural Resources, the Ministry of Livestock and Fisheries- General Directorate of Rangeland and Pasture, the Sudan Meteorological Authority and University of Khartoum to:

- Learn about **applications of Earth Observation (EO) in assessment and monitoring of climate vulnerability,** including for land health and climate change to support decision making for agricultural resilience.
- **Identify relevant stakeholders and existing platforms or online systems** in the country relevant to the project.

- Introduce **decision dashboards** and discuss possible dashboard **users and their needs**, visualization preferences and access capabilities.
- Identify exisiting **data and information** on climate and land health that is collected and held by various partners in the country and evaluate the quality and accessibility of this data and any gaps.
- Establish a **dashboard co-design team** and develop a roadmap for dashboard development.

A Miro board documenting the workshop can accessed here and the workshop report is available here

Prototype review meeting: As part of the co-design process for the Sudan dashboard, the stakeholders reviewed a prototype of the dashboard and provided feedback and suggestions on what they understood from the data presented on the dashboard, if there were additional information stakeholders needed to see to better understand and use the data, and who the users of the dashboard were and what they would use the data for. The minutes from the meeting are available here.

Monthly meetings with stakeholders in Sudan: The project held virtual monthly update meetings with stakeholders in Sudan to apprise them of the progress in the project activities as well as to plan for the next steps. Attendance to the meetings was commonly made up of representatives from the Ministry of Agriculture, NDC partnership, and the Higher Council for Environment and Natural resources. Other issues discussed in the meetings included: supporting the NDC partnerships with vulnerability maps for use in their reporting, hiring national consultants and their Terms of Reference, the need for data collection protocols and technology transfer among others.

In response to requests raised during the meetings, the project developed, for the NDC partnership, a vulnerability assessment map (Figure 6). This map is also part of the developed dashboard, where it is presented in an interactive format.

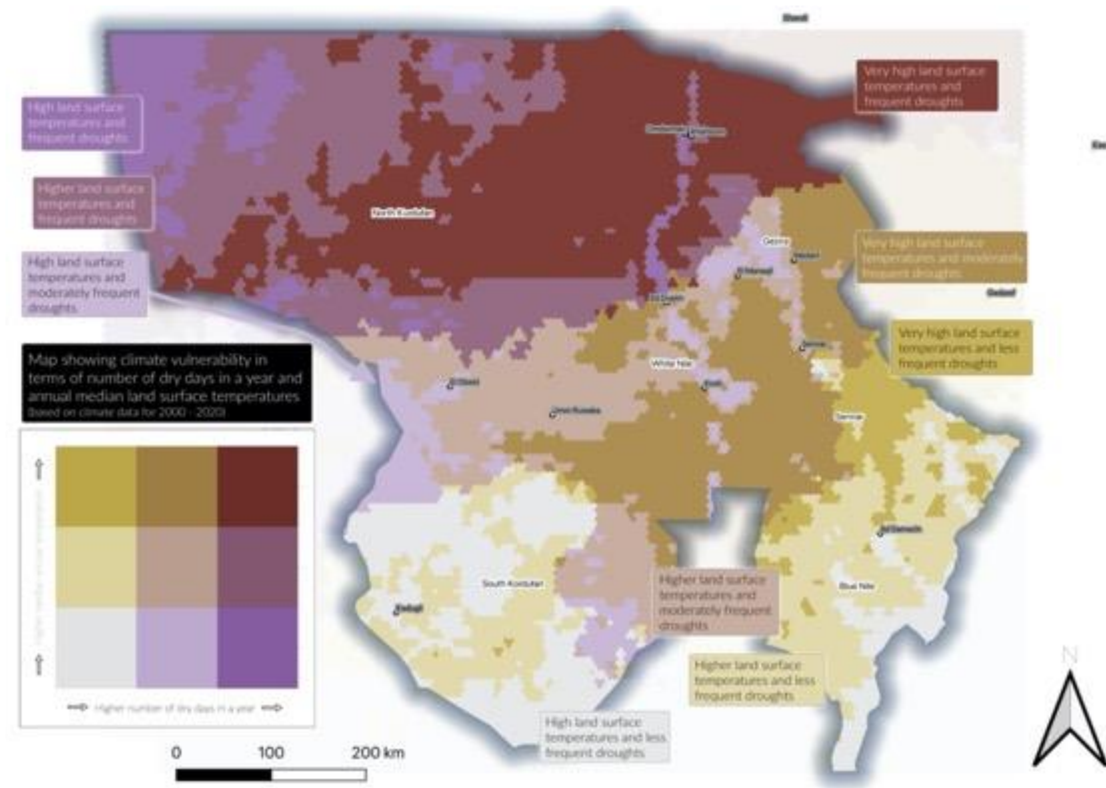

Figure 6: Map of the six states showing a composite climate vulnerability index based on a combination of the frequency of dry days in a year and high median land surface temperatures

The project also developed a protocol to provide guidelines for the process of collecting data, the type of data to be collected and format of the data needed for the Sudan dashboard. The protocol is available here. Furthermore, two national consultants identified by the Sudan national team were hired to support the project in collecting and collating data from the six states in which the project was implemented. Subsequent monthly meetings also focused on the data collected by the consultants. One of the consultants also provided in-country capacity development as outlined below.

Capacity development

Access to and use of evidence for decision making

Capacity development workshops were organized to support the Sudan team in terms of access to and use of data and evidence for decision making. The training workshops brought together over 20 participants from the Sudan Meteorological Authority, Ministry of Agriculture, National Centre for Information and the Higher Council for Environment and Natural Resources, and universities.

GIS data management, analysis and visualization

The first training workshop focused on *introducing stakeholders to remote sensing data analysis,* including how to use GIS software to analyze spatial data and data sharing principles and process between various institutions in Sudan. The workshop report is available here.

Data analysis using R Statistics

A second training workshop focused on *building the capacity to access and use the Interactive Sudan Climate Vulnerability Atlas,* including an introduction to the R Statistics and RStudio software used analyze the data visualized on the Interactive Sudan Climate Vulnerability Atlas. The workshop was officially opened by Dr. Elatib Ganawa, the project consultant, who led the workshop locally in Khartoum. He provided a background of the project and the previous capacity building trainings conducted on Geoportal Database Building, Prototype of the Climate Vulnerability Atlas and Earth Observation Monitoring. Dr. Ganawa emphasized how data sharing has been a big part of realizing the project objectives and expects that this training will further support improved data management. Dr. Tor-G Vågen gave a background on the Climate Vulnerability Analysis while emphasizing the importance of land health data for climate vulnerability, Earth Observation and R statistics to conduct data analysis.

One of the objectives of the training was to build capacity to access and use the Interactive Sudan Climate Vulnerability Atlas. This includesd an introduction to the R software used to develop and analyze the data visualized on the dashboard. Activities were facilitated by Dr. Amar and Mustafa with support from Dr. Vagen and Clinton Oyogo who led a hands-on session where they worked on the rainfall data to offer participants a practical experience, covering the use of R Statistics for GIS analysis and visualization.

Figure 7: Photo of the participants that took part in the data analysis training workshop in Khartoum 7-9 September, 2021.

Figure 8: Photos of participants taking part in the data analysis training workshop in Khartoum 7-9 September, 2021.

The participants were taken through an introduction to leaflet and mapping training session which consisted of definitions of terms and interactive coding exercises. The data used in the exercise was the temperature data for the project areas, including:

- Introduction to RMarkdown
- Introduction to the leaflet R library

- Brief introduction to spatial data analysis, including various types of spatial data
- Hands-on exercises:
  - Creation of basic maps using leaflet library
  - Importing shapefile data into R
  - Visualizing the shapefile on a leaflet map
  - Added layers to the map, color palettes and styling

At the end of the exercise the participants were able to create an RMarkdown notebook with steps on how to import and map temperature data and adding layers to the map (Figure 9).

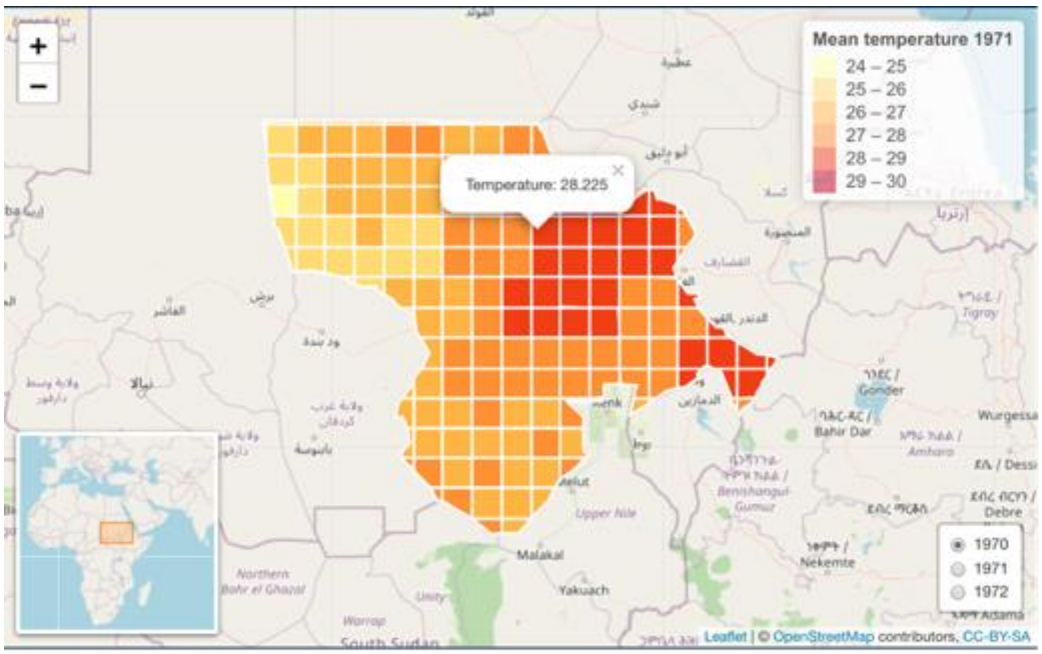

Figure 9: Map created by participants in the R Statistics capacity development workshop showing historical air temperature data for Sudan.

Once the participants had gained a basic understanding of R Statistics, an interactive session on data and decision-making was conducted. Participants highlighted their data realties in relation to climate vulnerability, within their various departments. Some of the issues that were emphasized include data sharing, data synthesis, data repositories, and financial resources to improve data quality.

Using the backdrop of the data realities shared, the participants were taken through an interactive session of the Interactive Sudan Climate Vulnerability Atlas. Emphasis was laid on how it can be leveraged to support decision making. Many participants found it useful for encouraging data sharing among their departments and complementary to existing and planned data repositories. They highlighted that the Atlas will be useful in supporting NDC implementation plans and other activities to be identified. Participants gave their feedback on various changes to improve the user-friendliness of the Interactive Sudan Climate Vulnerability Atlas, which are being implemented by the dashboard development team on a continuous basis.

An outcome of the data realities session was the identification of the need to bring decision makers from the various government entities to discuss information sharing and address the attendant barriers. There were suggestions that jointly developing a uniform data sharing protocol may go a long way in addressing some of these barriers related to information sharing. The proposed data sharing protocol will build on the guidelines for data collection developed earlier in the project. Participants noted that, in addition to high level political good-will, including junior and mid-level technical staff in data sharing conversations is also important to ensure follow through and sustainability. Participants highlighted that they will seek to explore experiences from other countries on data sharing, which can form part of a possible second phase of the project.

In terms of capacity building, participants noted that this training was akin to a training of the trainers' session, and they will seek to transfer the knowledge gained to their colleagues within their departments, to encourage using data for decision making. Additionally, they expressed their desire to build national experts in earth observation and to build capacity on the whole knowledge management value chain for the Atlas. The workshop report is available here. Participants in the workshop were from a number of national institutions, including:

- Ministry of Agriculture
- Higher Council for Environmental and Natural Resource management
- Remote Sensing Authority

Interactive decision dashboard integrating climate variables with soil and land health

The Interactive Sudan Climate Vulnerability Atlas was co-developed with the project partners in Sudan as part of the engagement process mentioned above (Section 3). The dashboard is available online HERE. It is still under active development and there is an ongoing dialog with the national partners focusing on the sustainability of the dashboard and next steps in terms of capacity development. Figure 10 shows the screenshot of the landing page for the dashboard.

Figure 10: A screenshot of the landing page for the Interactive Sudan Climate Vulnerability Atlas

Interactive Sudan Climate Vulnerability Atlas

Climate vulnerability

The climate vulnerability assessment is presented in the Interactive Sudan Climate Vulnerability Atlas as an interactive map that responds to users clicking on the map to highlight the climate vulnerability domain or group that is being clicked on (Figure 11) and then displaying a summary of the indicators and detailed time-series (Figure 12). The land surface temperature analysis also includes information on optimal temperature ranges for maize (*Zea mais*) and sorghum (*Sorghum bicolor*), allowing users to explore constraints to crop production in terms of temperatures across the six project states.

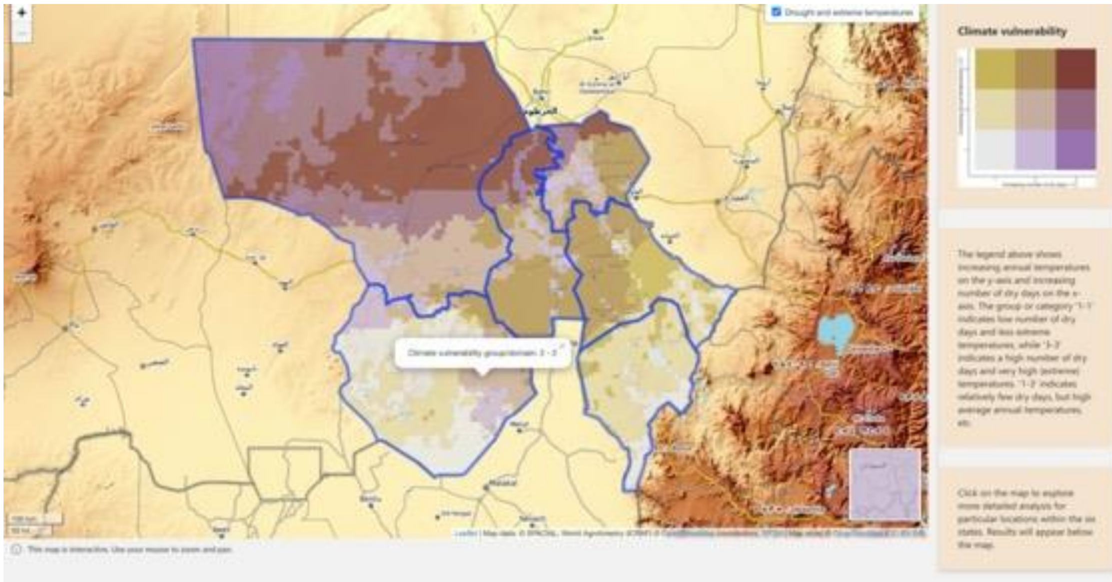

Figure 11: Map of the composite climate vulnerability map for the six project states from the Interactive Sudan Climate Vulnerability Atlas

Figure 12: Graphs showing summaries of dry days, rainy days, extreme rainfall events, and extreme temperatures, along with time-series graphs.

Historical information on air temperatures can be accessed as part of the Atlas, both in terms of temporal variations and trends over the period 1970 to 2002 and in the form of a spatial grid for each year. These assessments show a general trend of increasing temperatures on average over this period, as shown in Figure 13.

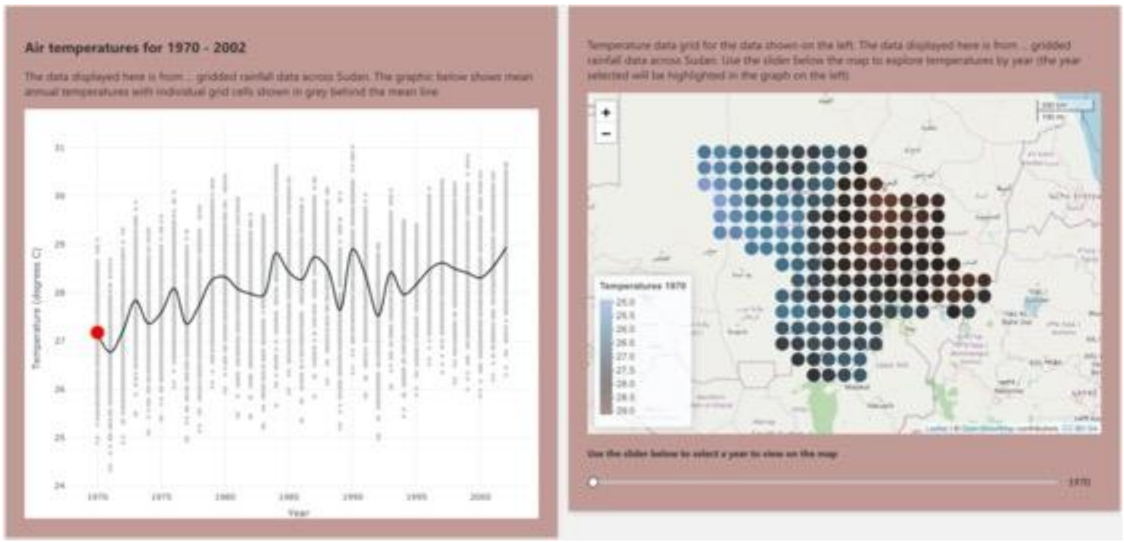

Figure 13: Air temperatures in the six project states, based on historical records.

Soil and land health

Land health is a key aspect of climate change vulnerability as it determines how well an ecosystem functions in terms of delivering important ecosystem services such as regulation of water, productivity, and biodiversity. In other words, land health is critical for climate change adaptation and for the adaptive capacity of agricultural systems in Sudan (Figure 14).

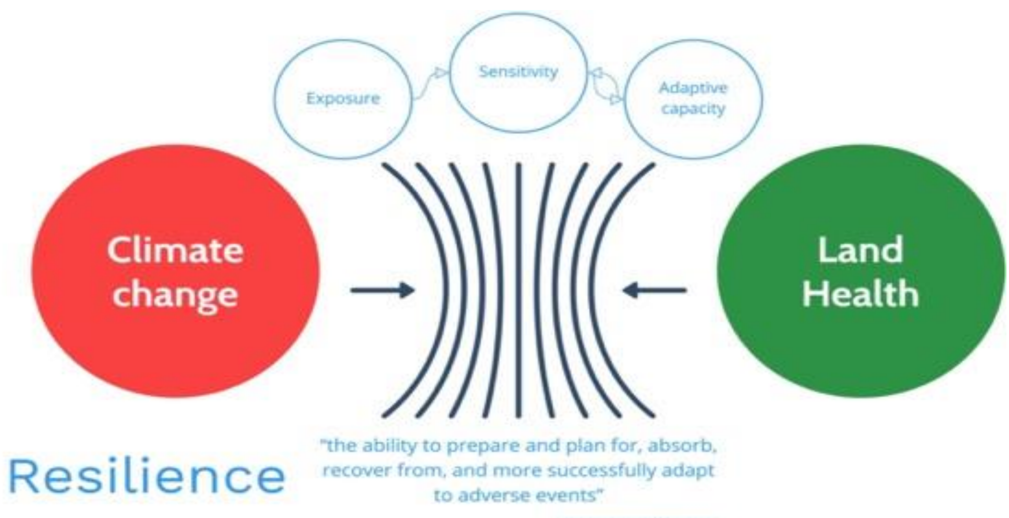

Figure 14: Land health is key for the resilience of ecosystems to the impacts of climate change, and for climate change adaptation.

Spatially explicit assessments and maps of land health indicators that are both accurate and conducted at sufficient spatial resolution to inform interventions and monitor change represent important resources for land managers and policy makers. For example, having the ability to identify areas that are highly constrained in terms of SOC or soil fertility is important for determining not only climate change vulnerability, but also for identifying important options for management to mitigate these constraints. Further, having access to multiple indicators simultaneously and at the same spatial scale (Figure 15) help deepen such insights and can be used to more effectively monitor the effectiveness of interventions over time.

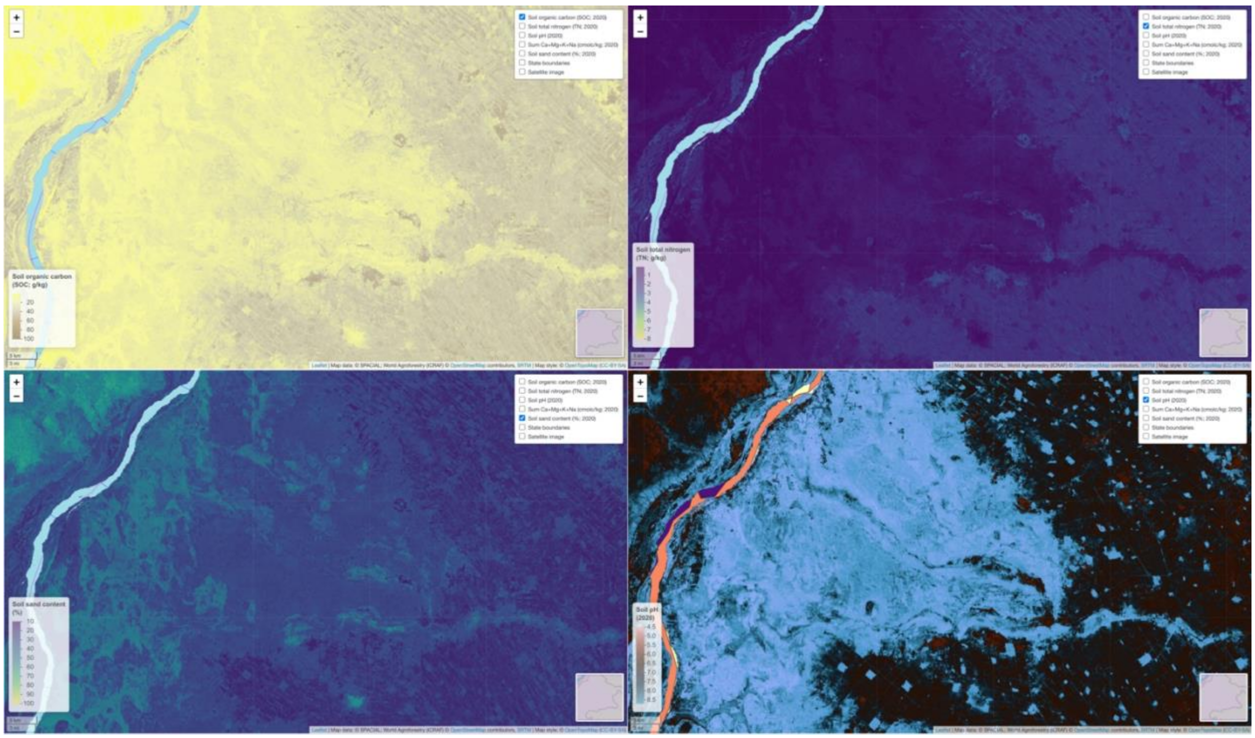

Figure 15: Land health indicator maps generated based on the LDSF for an area south of Bahri showing local variations in SOC (top-left), total soil nitrogen (top-right), soil texture (bottom-left), and soil pH (bottom-right). These maps were extracted from the Interactive Sudan Climate Vulnerability Atlas and similar assessments and comparisons can be made for any location within the six project states.

In the Interactive Sudan Climate Vulnerability Atlas, users can also explore interactions between soil and land health indicators, as illustrated in the graph in Figure 16. Users can then select points in this graph and these are highlighted on the indicator map panel. In other words, the Atlas can be used as a tool to identify specific areas that should be targeted for management interventions based on the indicator maps.

Figure 16: Graph showing interactions between SOC and pH for part of the area south of Bahri in the maps above.

The users can also explore the variation in annual vegetation cover for the period from 2000 to 2020. Figure 17 shows the vegetation cover across the six states as visualized on the dashboard.

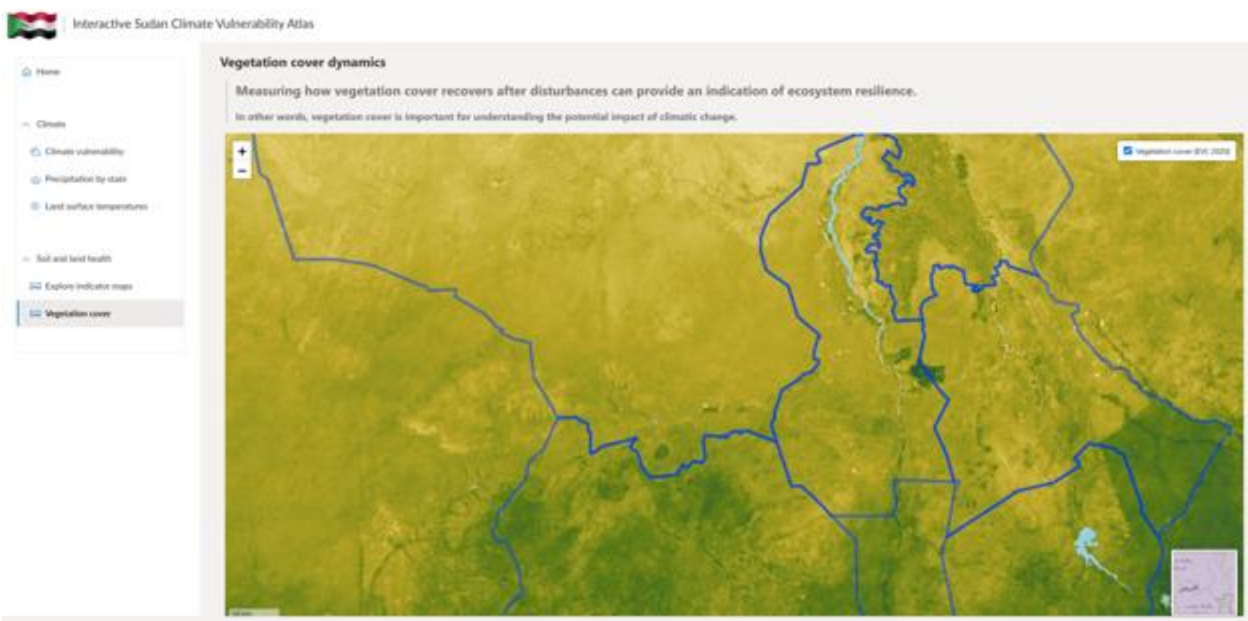

Figure 17: vegetation cover map of the six states visualized on the Sudan Climate Vulnerability Atlas.

Conclusions and next steps

There are significant capacity gaps in-country for the processing, analysis and use of data and evidence in decision making. Additional technical support to the partners is needed to build the required capacity. This was something that the partners in Sudan identified as key next steps to further enhance the Interactive Sudan Climate Vulnerability Atlas and for high level buy-in and support. Mechanisms for data sharing across departments are generally absent. This means that is remains challenging to access and synthesize data across departments and sectors, such as for example meteorological data and agricultural data. An important next step is therefore to establish protocols and mechanisms that enable data sharing to effectively assess and generate management recommendations to enhance climate resilience in Sudan.

Earth-observing satellites can play a key role in mapping and monitoring climate variables and climate vulnerability, helping to bridge some of the gaps identified in the project in terms of available climate data in Sudan. Earth observation also has a large potential for predictive modeling and mapping of land degradation, soil functional properties such as soil organic carbon, soil pH or acidity, soil fertility parameters and soil texture. With a combination of these assessments and maps and earth observation based climate data, the Interactive Sudan Climate Vulnerability Atlas is helping stakeholders in Sudan to make more informed decisions related to multiple aspects of climate change vulnerability in the country.

The Interactive Sudan Climate Vulnerability Atlas builds on recent developments in land health surveillance from reflectance-corrected satellite imagery and field-sampled spectral libraries using the LDSF for biophysical characterization of the land surface. These advances present opportunities to revolutionize the way in which spatial resources are monitored, analyzed and predicted. This in turn greatly enhances the potential for providing evidence-based and timely decision support at multiple spatial scales, and represents a real opportunity to enable science-based monitoring approaches that can be applied in agricultural landscapes and for environmental management in general.

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