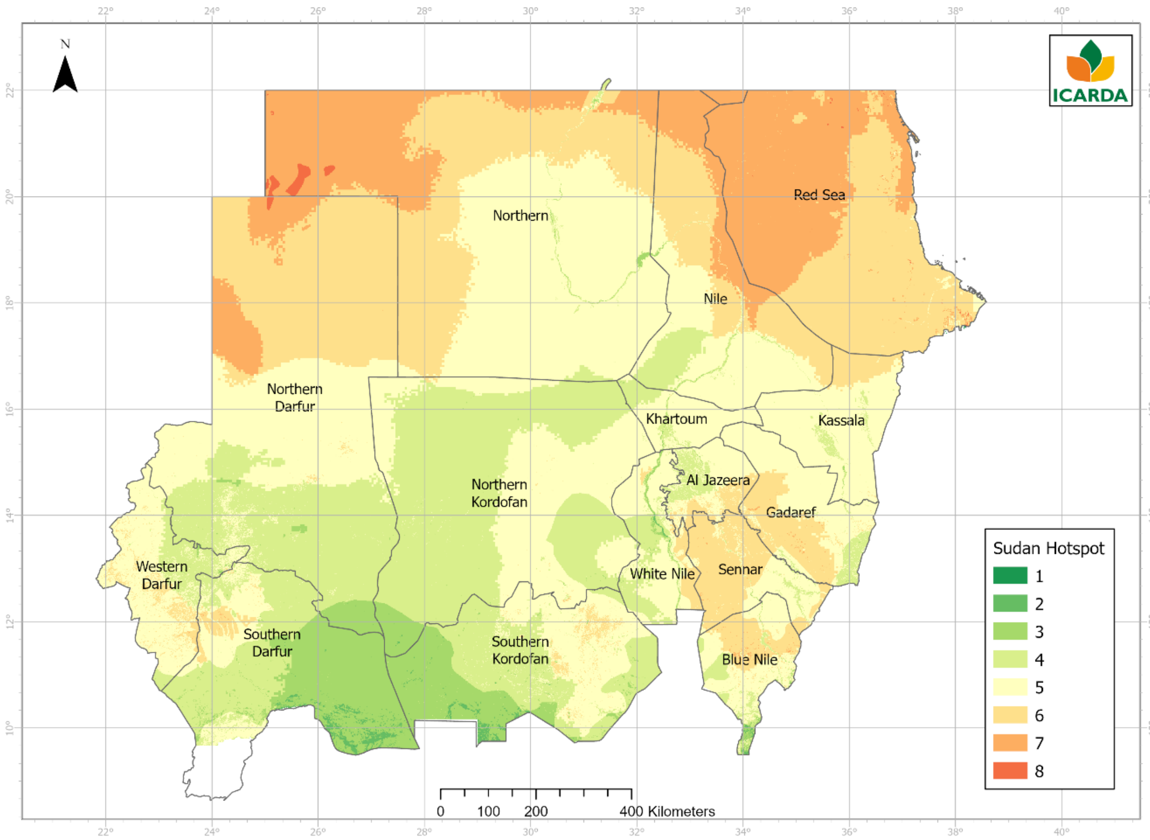
INITIATIVE ON
Fragility to Resilience in
Central and West Asia

# Report on: Mapping natural resource (soil, weather, agro-biodiversity) to identify hot-spots and suitable areas in Sudan




*Prepared by: Layal Atassi, Krishna Devkota, and Mina Devkota*

## Summary

This report summarizes the trend in average temperature, precipitation over time and space from different region in Sudan. Also, it includes identification of hot spots for various climatic and soil parameters such as long-term rainfall patterns, rainfall variability, areas prone to drought, as well as average, maximum, and minimum temperatures essential for wheat cultivation. Furthermore, parameters related to soil fertility, such as texture, soil organic carbon content, slope/elevation, and soil salinity, are considered. Soil-water resources, including groundwater availability, dam locations, and soil displacement by water, are also evaluated. Vegetation indices such as NDVI (Normalized Difference Vegetation Index) and ground cover are mapped for different region in Sudan.

# Table of Contents

**List of Figures**

**List of Tables**

# Mapping natural resources (soil, weather, agro-biodiversity) to identify hot-spots and suitable areas in Sudan

## Introduction

The Fragility to Resilience (F2R) in Central and West Asia and North Africa (CWANA) (F2R-CWANA) Initiative, part of OneCGIAR, is dedicated to agricultural research and development, especially addressing the unique challenges and opportunities within the region. One of the key activities of the F2R-CWANA initiative involves mapping natural resources, focusing on identifying climatic hot spots relevant to wheat cultivation in Egypt, Uzbekistan, Morocco, Lebanon, and Sudan within the CWANA region. This effort encompasses a detailed analysis of climatic variables such as long-term rainfall patterns, rainfall variability, areas susceptible to drought, and temperature metrics (including average, maximum, and minimum temperatures), along with trends in rainfall and temperature across different times and locations. Additionally, soil fertility factors, including soil texture, organic carbon content, slope/elevation, and salinity, were assessed. The study also covered soil-water resources, highlighting groundwater availability, dams, and soil erosion by water, alongside vegetation indices and ground cover metrics, such as NDVI and overall vegetation coverage. Ultimately, after evaluating 13 critical climate, soil, and water parameters, hotspot and suitability maps were created. The project leveraged remote sensing data from Sentinel-2, Landsat-8, and MODIS satellites, complemented by data from various sources including the FAO (for soil salinity and organic carbon), ISRIC (for soil parameters), and ESRI (for 10-m land use and land cover), to map the specific natural resources and climatic hot spots for Sudan.

## Geospatial and temporal mapping of natural resources

### 1. Climatic parameters

#### 1.1. Long-term rainfall, rainfall variability, and dry/drought-prone areas

Between 2015 and 2021, the average annual rainfall during the wheat cultivation season (November to April) across different regions of Sudan showed a broad range, from virtually none to 800 mm, as depicted in Figure 1. The southern parts of the country, particularly in the Blue Nile state, experienced the highest levels of rainfall, with amounts varying between approximately 400 and 800 mm. Similarly, substantial rainfall, peaking at around 700 mm, was recorded in regions such as West Darfur, South Darfur, Southern Kordofan, Sennar, and Gadaref. Conversely, the northern areas of Sudan, including the Northern, Nile, Red Sea, and Northern Darfur states, registered the lowest rainfall, with totals under 25 mm.

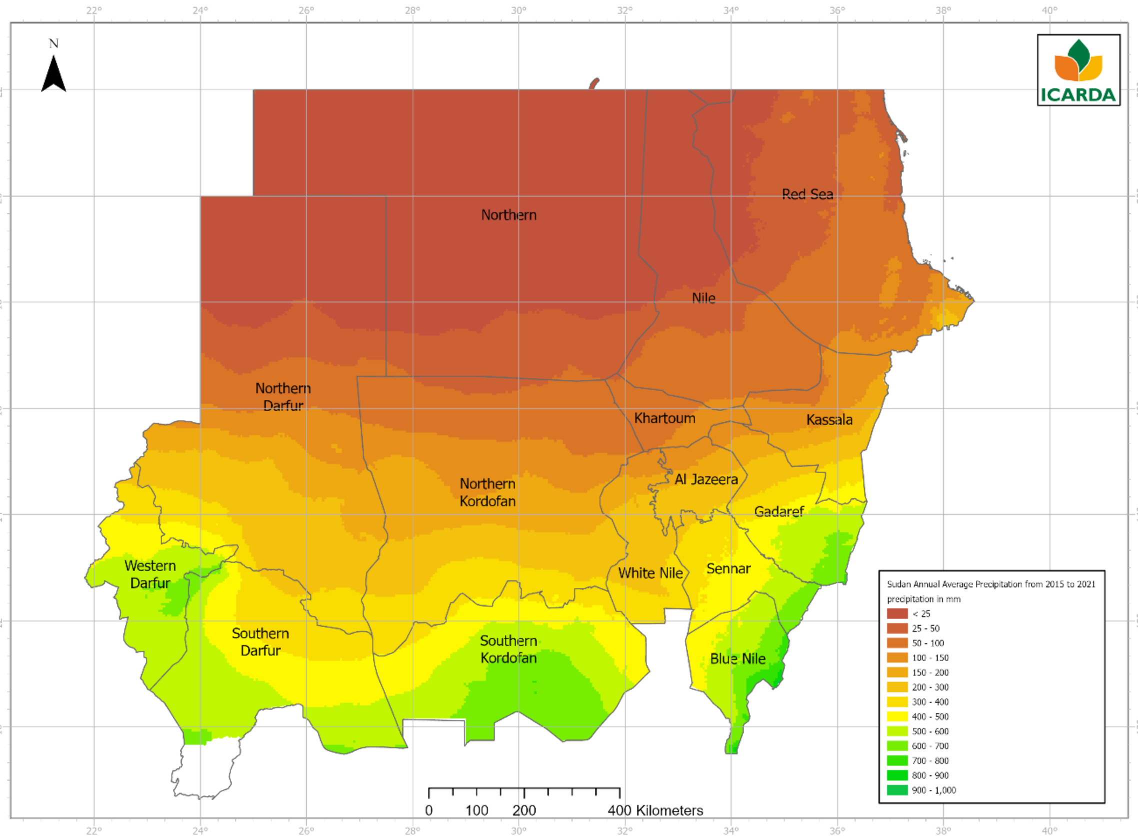



*Figure 1. Map of annual average precipitation in Sudan from 2015 to 2021 (Data source: TerraClimate).*

## 1.2. Temperature

From 2015 to 2021, temperature data for Sudan were analyzed using the TerraClimate database through the Google Earth Engine code editor, focusing on datasets with a 250-meter spatial resolution that were adjusted to fit within the country's borders. Over these years, the annual maximum temperatures varied between 23.9°C and 39.38°C, as shown in Figure 2. The highest temperatures were predominantly recorded in Kassala, Nile, Al Jazeera, and Sennar states, where they ranged from 37.5°C to 39.4°C. The lowest temperatures were observed in the Red Sea and in parts of western and northern Darfur states, with temperatures between 23.9°C and 25°C. Minimum temperatures across the country ranged from 7.3°C to 25.3°C, detailed in Figure 3, with the coldest readings below 7.3°C to 10°C found in Western and Southern Darfur. During the same period, the average annual temperature across Sudan fluctuated from 15.8°C in select areas of the Red Sea, Western Darfur, and Southern Darfur to 31.68°C in Kassala and Nile states, as illustrated in Figure 4.

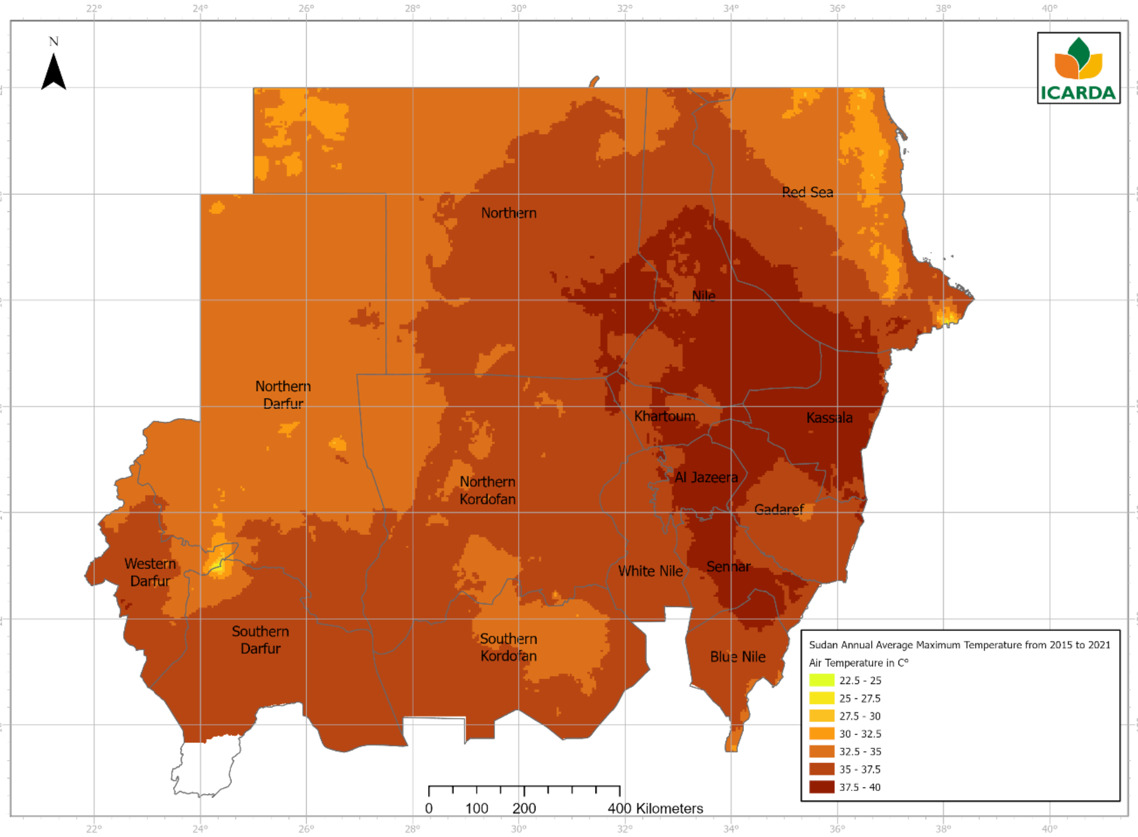



*Figure 2. Maximum temperature (°C) from 2015 to 2021 in Sudan (Data source: TerraClimate).*

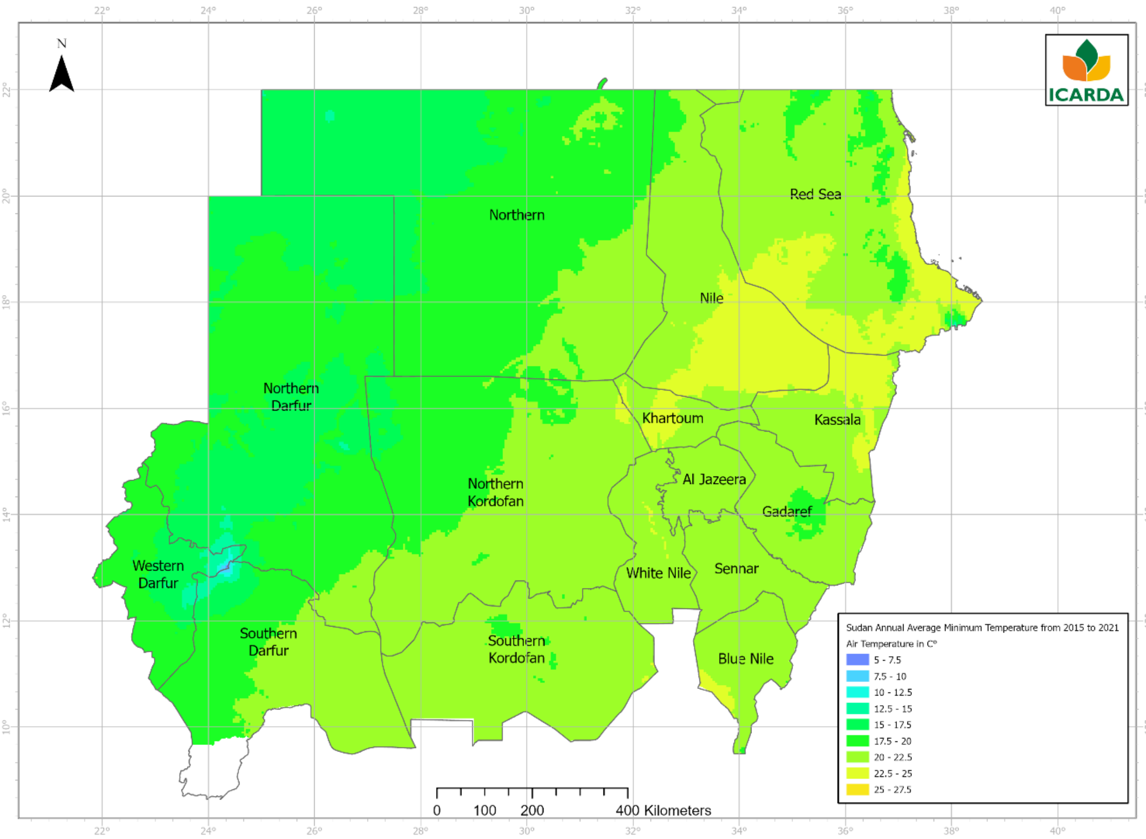



*Figure 3. Minimum temperature (°C) from 2015 to 2021 in Sudan (Data source: TerraClimate).*

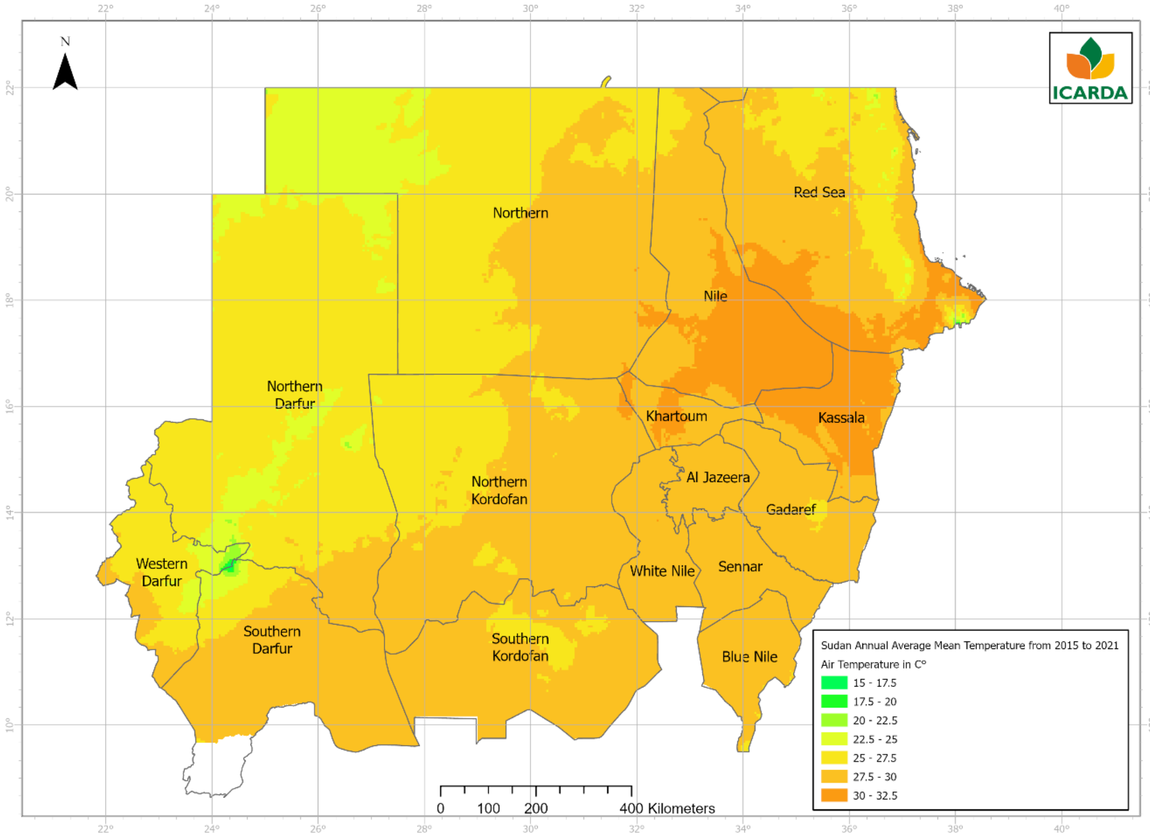



*Figure 4. Average annual temperature (°C) from 2015 to 2021 in Sudan (Data source: TerraClimate)*

## 1.3. Change in climate change parameters.

Climate change indicators, including variations in rainfall and temperature extremes, were analyzed using data from the TerraClimate database via the Google Earth Engine code editor. This analysis utilized records from 2000 to 2021 to determine trends in these climatic factors through time series analysis, employing a linear trend model. The generated map visualizes the changes per pixel across the last two decades for each climatic parameter.

In the southern regions of Sudan, encompassing Southern Darfur, Blue Nile, Sennar, and Gadaref states, precipitation has diminished by approximately 15 to 21 mm, indicating a trend towards drier conditions over the past 20 years, as depicted in Figure 5. Conversely, in the southwestern parts of Northern Darfur state, rainfall has seen an increase of about 5 to 6 mm during the same period. Meanwhile, the northern parts of Sudan have experienced minimal or no change in rainfall, with a slight increase of around 2.5 mm over the past two decades.

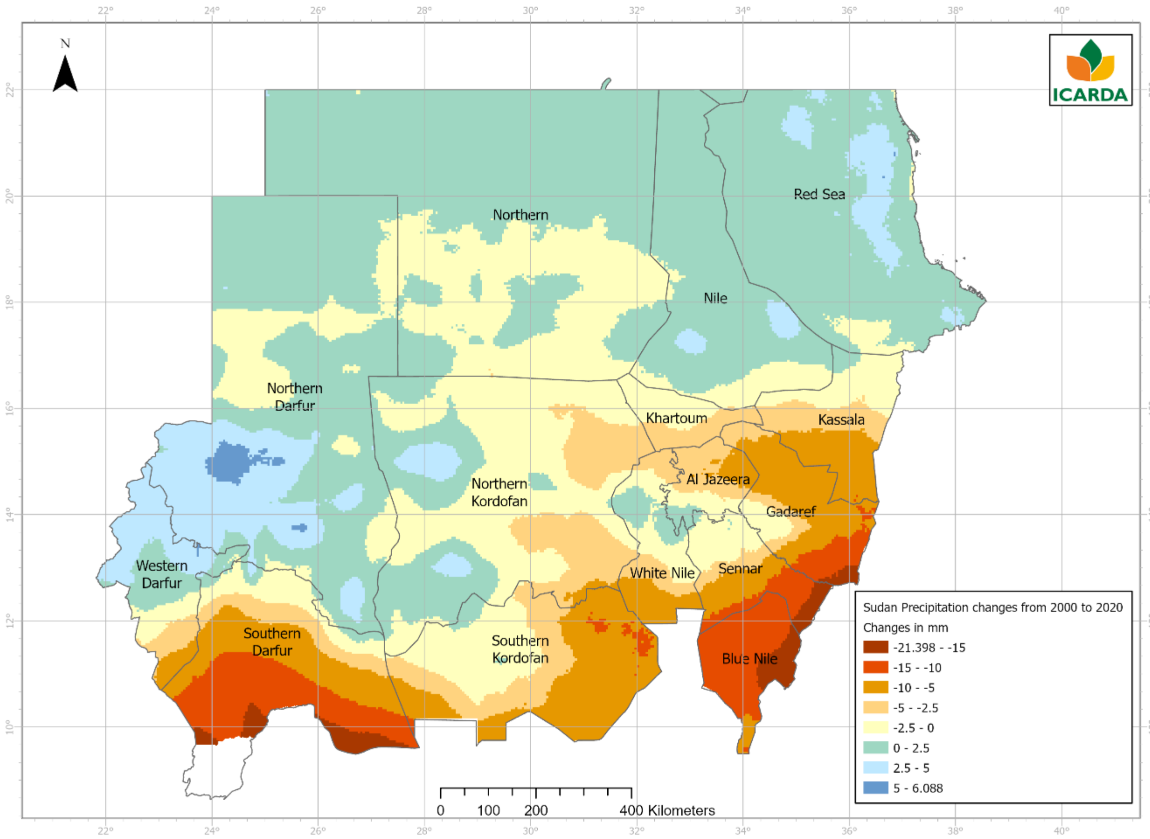



*Figure 5. Precipitation changes in Sudan from 2000 to 2021 (Data source: TerraClimate).*

The southern regions of Sudan have witnessed a notable rise in maximum temperatures, with the most significant increases observed in the Red Sea and Northern Darfur state, where temperatures have climbed by 1 to 1.3°C over the past two decades. Elsewhere in the country, the increase has been minimal to moderate, with some areas showing a temperature rise of up to 0.5°C, highlighted in yellow on the map (Fig. 6).

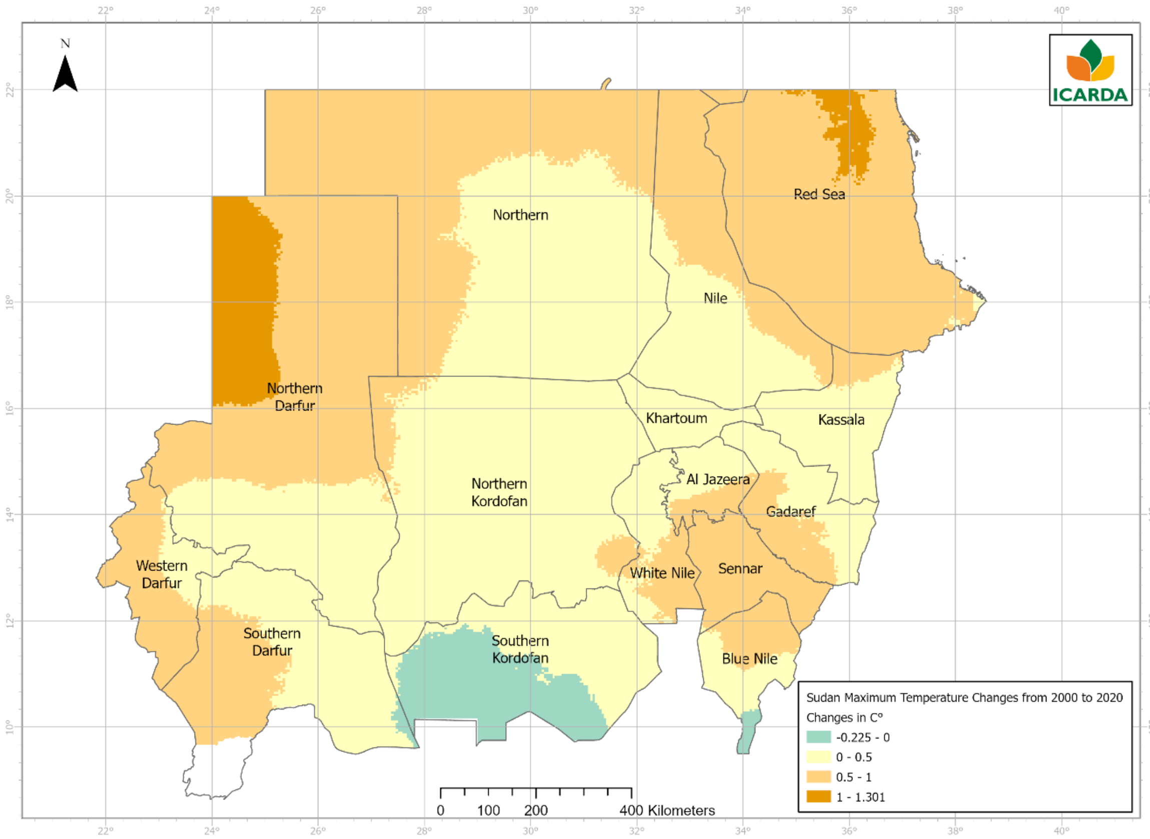



*Figure 6. Maximum temperature change in Sudan from 2000 to 2021 (Data source: TerraClimate).*

In the eastern parts of Sudan, particularly in the East Red Sea, Sennar, Gadaref, and Blue Nile states, the minimum temperature has risen by approximately 1 to 1.3°C, depicted in orange on the map. Across the rest of the country, the increase in minimum temperature has been negligible or slight, registering around 0.5°C, which is shown in yellow color on the map for the last two decades (Fig. 7).

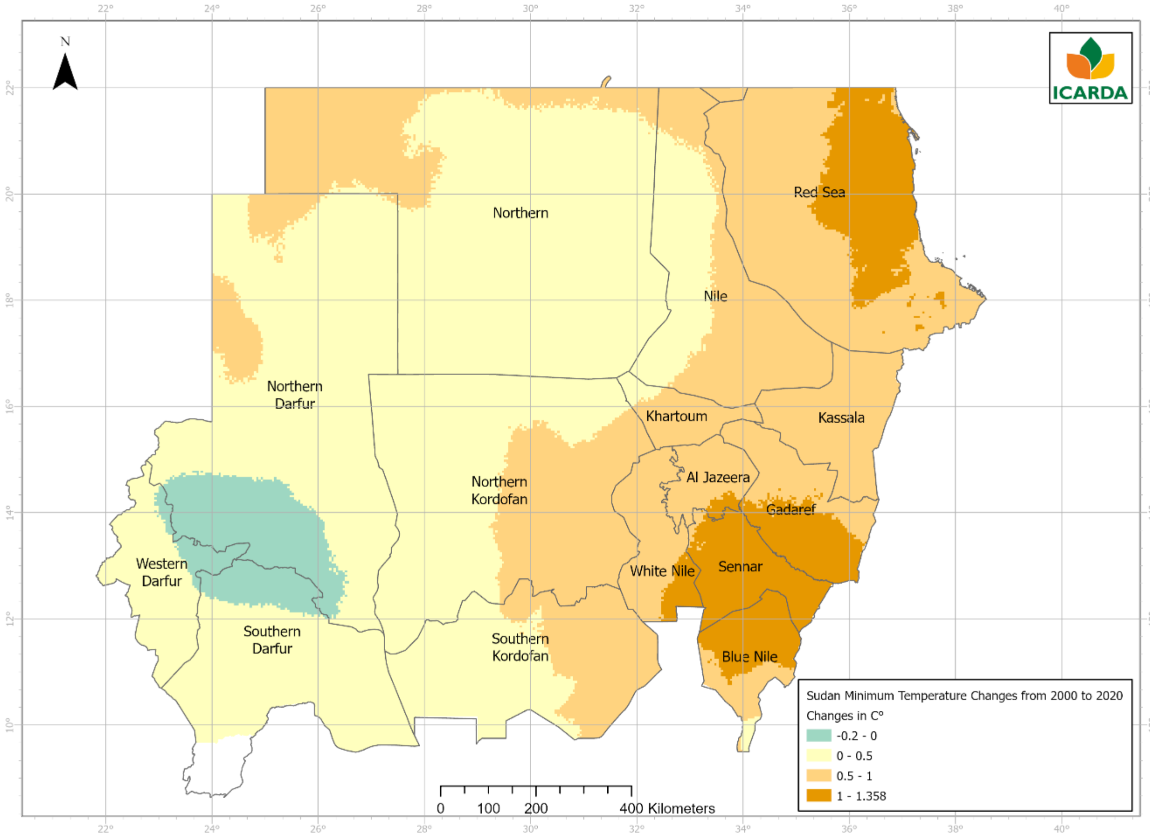



*Figure 7.Annual minimum temperature change in Sudan from 2000 to 2021 (Data source: TerraClimate).*

## 2. Soil type, soil fertility indicators, and other soil constraints

### 2.1. Soil texture

The soil texture across Sudan was delineated utilizing the Harmonized World Soil Database (HWSD) by the FAO, which adheres to the USDA soil classification system. By applying the zonal statistic tool in ArcGIS Pro to the HWSD's raster data on soil texture, the area covered by different soil textures within each state of Sudan was quantified.

Sudan's landscape is predominantly covered by sand, constituting 46.3% of its area, with sandy loam making up 18.33%, followed by sandy clay loam at 13.5%, and clay covering approximately 10.5%, as illustrated in Figure 8. In regions such as Al Jazeera, White Nile, River Nile, and Northern State, wheat cultivation is primarily conducted on large, irrigated farms (ADBG 2023). Table 1 presents the breakdown of soil texture areas in hectares for each Sudanese state, highlighting that Al Jazeera predominantly features clay soils, accounting for about 1,966,999 ha, along with sandy clay loam (218,708 ha), clay loam (175,607 ha), sandy clay (18,571 ha), sandy loam (13,498 ha), and loam sand (328 ha). The White Nile state is mainly characterized by clay soils, encompassing 1,310,944 ha, whereas the Nile state is largely covered by sand, amounting to 7,735,053 ha, followed by sandy clay loam covering 2,086,312 ha.

*Table 1. Soil texture area (ha) in different states of Sudan (Source: FAO HWSD database)*

| State | clay | sandy clay | clay loam | sandy clay loam | loam | sandy loam | loamy sand | sand |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| AL JAZEERA | 1966999 | 18571.4 | 175607.1 | 218708.7 | 0.0 | 13499.0 | 328.3 | 0.0 |
| BLUE NILE | 2420378 | 569.1 | 1261703.4 | 108845.5 | 787.9 | 0.0 | 0.0 | 0.0 |
| KHARTOUM | 11972 | 23370.1 | 87532.7 | 803662.8 | 251.7 | 532249.5 | 140494.5 | 585736.5 |
| NORTHERN | 1007 | 1034.2 | 41460.0 | 252508.1 | 114.9 | 786256.9 | 792817.6 | 34398700.5 |
| NORTHERN DARFUR | 449 | 3956.1 | 235868.3 | 2178501.5 | 4049.1 | 4838255.2 | 1744296.1 | 22648534.2 |
| NILE | 16842 | 15857.3 | 108407.7 | 2086312.3 | 27.4 | 1981537.9 | 993480.2 | 7735053.6 |
| SENNAR | 3799714 | 1723.6 | 216892.0 | 22024.1 | 0.0 | 246.2 | 0.0 | 0.0 |
| SOUTHERN DARFUR | 317546 | 34926.6 | 1485249.2 | 6233257.6 | 20951.6 | 5592945.1 | 120768.6 | 2670.2 |
| WESTERN DARFUR | 5740 | 3480.1 | 307954.1 | 3407680.4 | 257.2 | 1717911.0 | 70115.9 | 61525.2 |
| WHITE NILE | 1310944 | 47489.9 | 667846.7 | 892678.3 | 0.0 | 836252.9 | 157205.4 | 94739.1 |
| SOUTHERN KORDOFAN | 3748936 | 85612.1 | 3153684.0 | 4284610.9 | 4142.2 | 1545012.4 | 17799.8 | 5.5 |
| RED SEA | 27 | 383.0 | 12623.5 | 1188687.4 | 18894.2 | 6677689.8 | 4127071.7 | 8343881.2 |
| KASSALA | 1318857 | 43068.7 | 707960.6 | 2253739.1 | 306.4 | 871447.7 | 181161.0 | 12929.9 |
| NORTHERN KORDOFAN | 120697 | 2949.3 | 141802.2 | 858764.0 | 1209.3 | 8628120.4 | 2572308.5 | 11933133.0 |
| GADAREF | 4468798 | 15518.1 | 850014.5 | 339679.7 | 93.0 | 1887.8 | 0.0 | 0.0 |

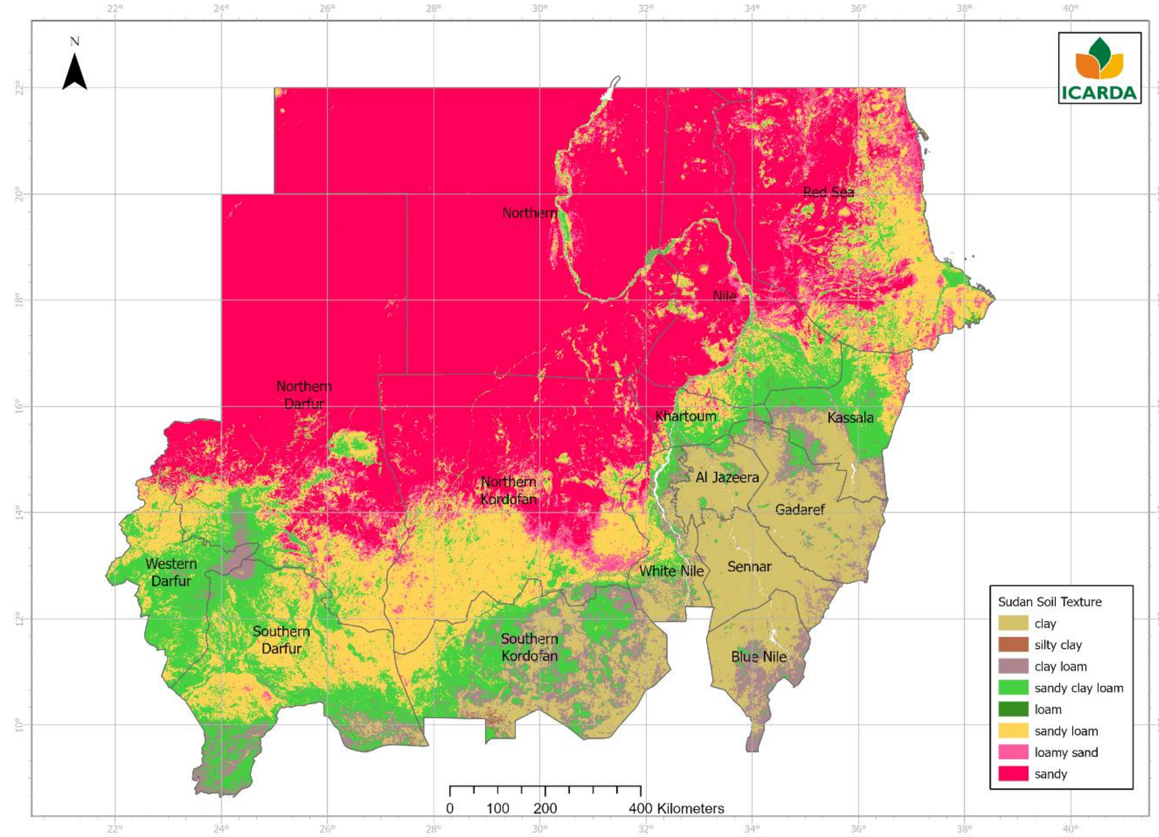



*Figure 8. Sudan soil textural classes (Data source: FAO HWSD).*

## 2.2. Slope/Elevation

The elevation and slope characteristics of Sudan were obtained from the SRTM30 Shuttle Radar Topography Mission data, which offers a resolution of 1 arc-second (roughly 30 meters) and was processed using the ArcGIS Pro platform. The SRTM30 data encompasses all terrestrial areas situated between 60° N and 56° S latitude, covering approximately 80% of the Earth's total land surface. This digital elevation dataset is the result of an international research collaboration, employing digital elevation models for its creation. Unlike some other datasets that may have unfilled gaps or use commercially sourced data to fill voids, this dataset has been enhanced through a void-filling process utilizing open-source data, including ASTER GDEM2, GMTED2010, and NED.

Sudan’s topography shows limited variation in elevation across most of the country, with notable exceptions being a few mountainous regions such as Jebel Marra, the Nuba Mountains, and the Red Sea Mountains, where the highest point reaches approximately 2908 meters above sea level. The majority of Sudan's landscape is relatively flat, featuring slopes of less than 5%, except in the aforementioned mountainous areas. This topographical variation is depicted in the slope map presented in Figure 9.

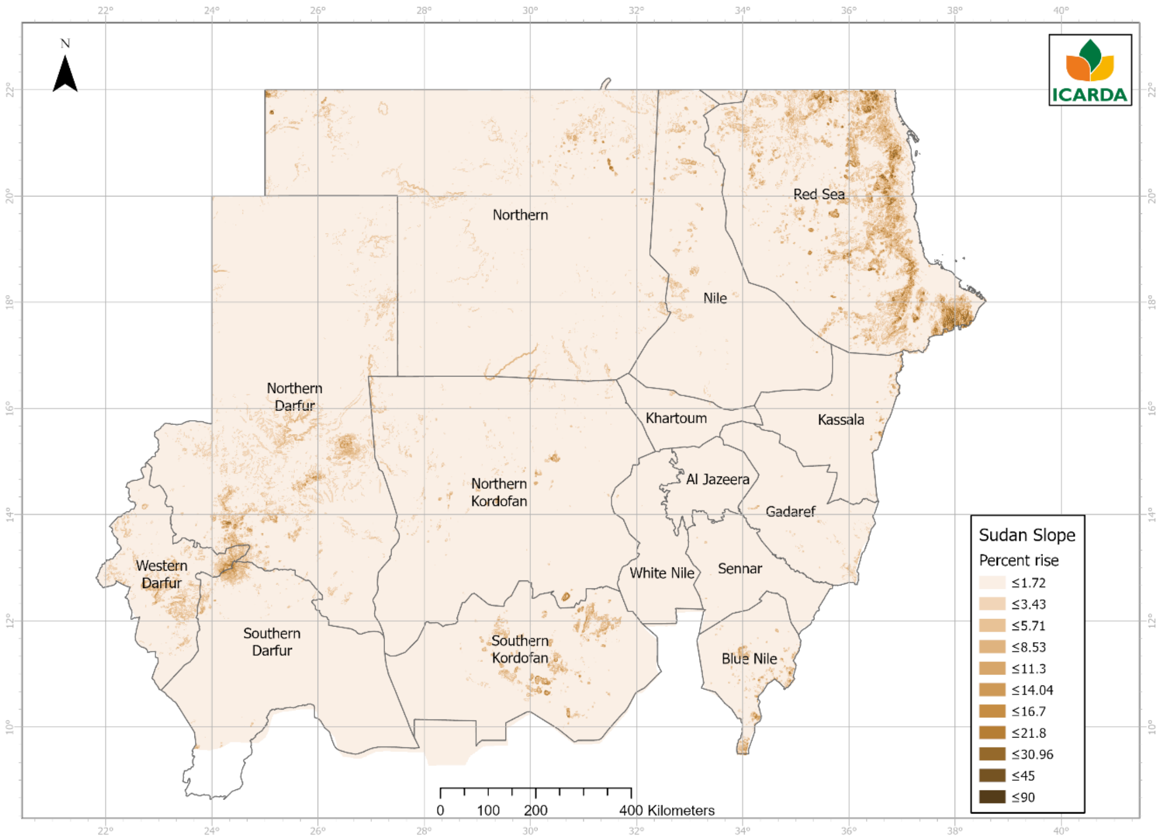



*Figure 9. Slope in (%) for different states of Sudan (Data source: derived from SRTM30 Shuttle Radar Topography Mission).*

## 2.3. Soil organic carbon

Soil organic carbon (SOC) content across various soil layers is quantified in grams per kilogram (g/kg), with the ISRIC's global soil organic carbon map marking a pioneering achievement as the first of its kind produced through a collaborative and inclusive process with input from member countries. This groundbreaking map was developed under the supervision of the Intergovernmental Technical Panel on Soils and the Global Soil Partnership Secretariat. Member countries reached a consensus on the methodology for creating the map and received training in contemporary tools and techniques for crafting their national maps. Following this, the Global Soil Partnership consolidated these national contributions into the final map, implementing a comprehensive harmonization process to ensure consistency and accuracy across the global dataset.

The SOC map for Sudan reveals that SOC levels vary from 1.9 to 71.3 grams per kilogram across the country. Areas with the highest SOC content, exceeding 30 g/kg, are predominantly located around the peak regions of Jebel Marra. Furthermore, regions with SOC content greater than 14 g/kg in the top 30 cm of soil are primarily found in mountainous areas. In contrast, the remainder of Sudan is characterized by lower SOC levels, as depicted in Figure 10.

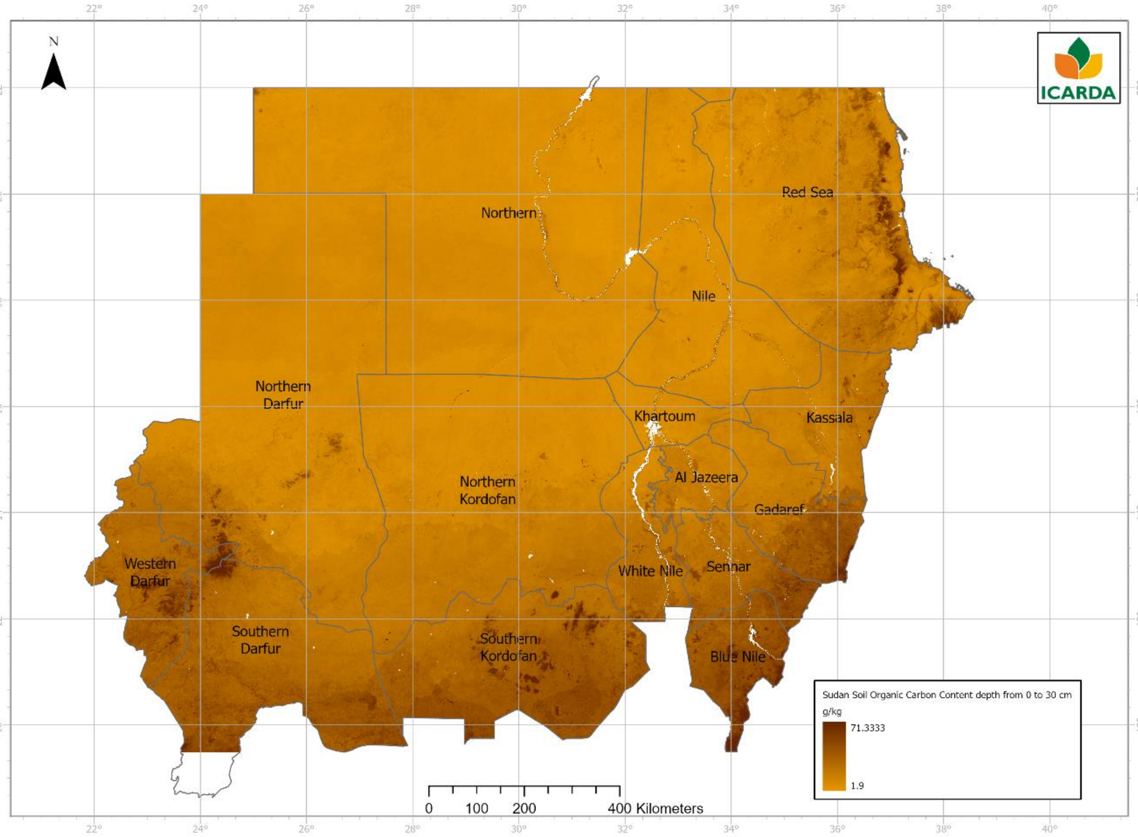



*Figure 10. Soil organic carbon (g/kg soil) content at 0-30 cm soil profile in Sudan (Data source: ISRIC digital soil data).*

## 2.4. Soil salinity

Soil salinity data for Sudan was sourced from the Harmonized World Soil Database (HWSD), a comprehensive 30-arc-second (about 100 m) raster database that includes more than 15,000 distinct soil mapping units. The HWSD compiles updated soil information from global sources, such as SOTER, ESD, the Soil Map of China, and WISE, at a scale of 1:5,000,000. This database is a collaborative effort among the FAO, IIASA, ISRIC-World Soil Information, the Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC), resulting in a raster database with 21,600 rows and 43,200 columns, linked to harmonized soil property data. Utilizing the ArcGIS platform, the soil salinity parameter, measured as electrical conductivity (EC) in dS/m, was extracted by associating attribute data with the raster map. EC values, which can approximate soil salt content, are obtained from measurements in a saturated soil paste or a diluted soil-water suspension. Based on agronomic thresholds outlined in the HWSD, soil salinity is categorized into four levels: very low (less than 2 dS/m), low (2 to 4 dS/m), moderate (4 to 8 dS/m), and high (8 to 16 dS/m).

In Sudan, soil salinity values span from 0 to 11.9 dS/m. The majority of the country exhibits very low salinity levels, with the highest salinity recorded in the Southern Darfur state, covering an area of 982,646 hectares. The Northern, Nile, Al Jazeera, and White Nile states, which are key regions for wheat cultivation, all display very low salinity levels, as indicated in Figure 11 and Table 2.

*Table 2. Area in (ha) under different categories of soil salinity in different states of Sudan*

| State | Very low (<2 dS/m) | Low (2-8 dS/m) | Moderate (4 to 8 dS/m) | High (>8 dS/m) |
|---|---|---|---|---|
| Al Jazeera | 2406623.58 | 0.00 | 0.00 | 0.00 |
| Blue Nile | 3820446.00 | 0.00 | 0.00 | 0.00 |
| Khartoum | 2202285.14 | 0.00 | 0.00 | 0.00 |
| Northern | 36152670.87 | 0.00 | 238569.95 | 0.00 |
| Northern Darfur | 31611962.50 | 0.00 | 38959.13 | 0.00 |
| Nile | 12977242.07 | 0.00 | 0.00 | 0.00 |
| Sennar | 4064706.60 | 0.00 | 0.00 | 0.00 |
| Southern Darfur | 12821580.65 | 0.00 | 0.00 | 982645.54 |
| Western Darfur | 5479316.95 | 0.00 | 0.00 | 90963.00 |
| White Nile | 4080552.90 | 0.00 | 33706.21 | 0.00 |
| Southern Kordofan | 12835938.62 | 0.00 | 0.00 | 0.00 |
| Red Sea | 20273367.66 | 65486.36 | 0.00 | 0.00 |
| Kassala | 5405338.38 | 0.00 | 0.00 | 0.00 |
| Northern Kordofan | 24264008.14 | 0.00 | 0.00 | 0.00 |
| Gadaref | 5678052.28 | 0.00 | 0.00 | 0.00 |

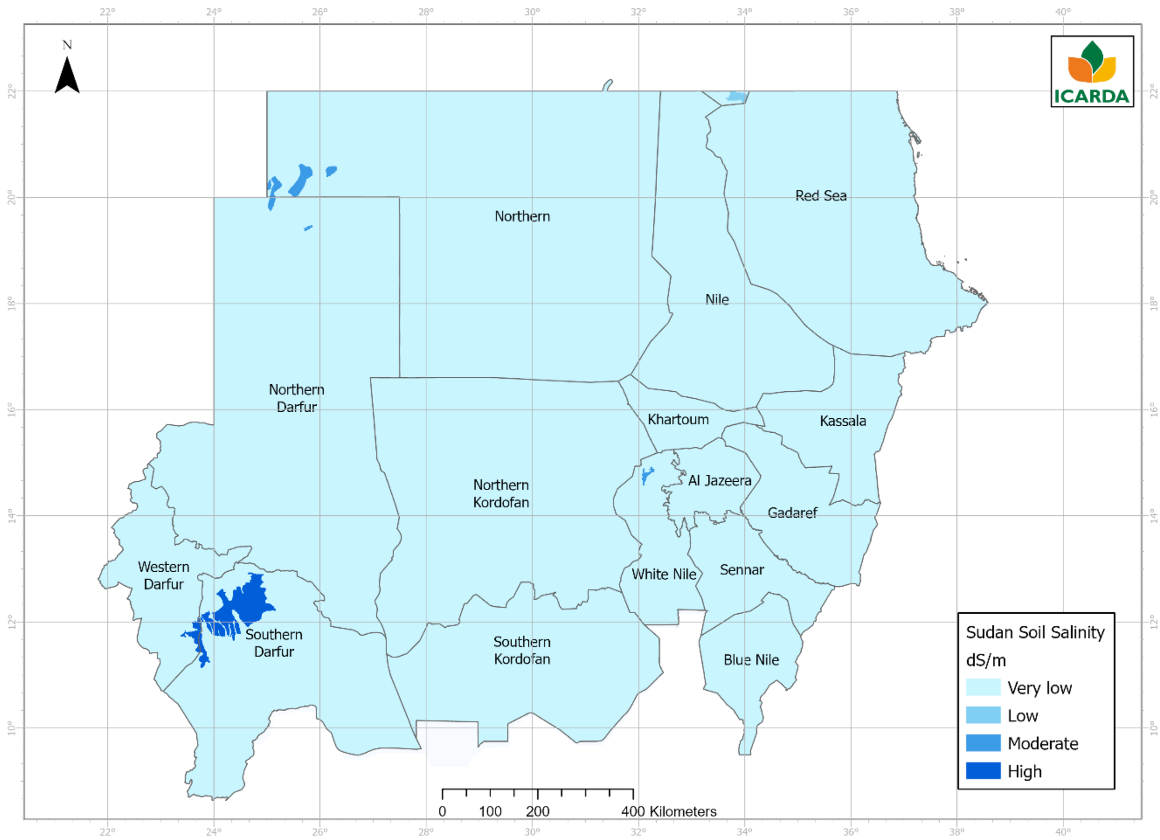



*Figure 11. Different categories of soil salinity in different states of Sudan (Data source: HWSD, FAO).*

## 2.5. Soil displacement by water

Data on soil displacement due to water erosion for Sudan in 2019, measured in megagrams per hectare per year (Mg ha−1 yr−1), was sourced from the European Soil Data Centre (ESDAC), utilizing the Global Soil Erosion map with a resolution of 25 km. This map is based on Version 1.1 of the JRC/UniBasel "RUSLE-based Global Soil Erosion Modelling platform (GloSEM)" (Borrelli et al. 2013). Figure 12 displays the soil displacement by water for Sudan, highlighting areas of low soil erosion, particularly around the Nile River and in the southern regions of Sudan, where the soil erosion rate is under 1 Mg ha−1 yr−1. Table 3 details the extent in hectares of various soil erosion categories across each Sudanese state. Notably, the Al Jazeera state, which hosts the largest wheat cultivation area, encompasses 171,304.25 hectares with soil erosion rates less than 1 Mg $ha^{-1}$ $yr^{-1}$.

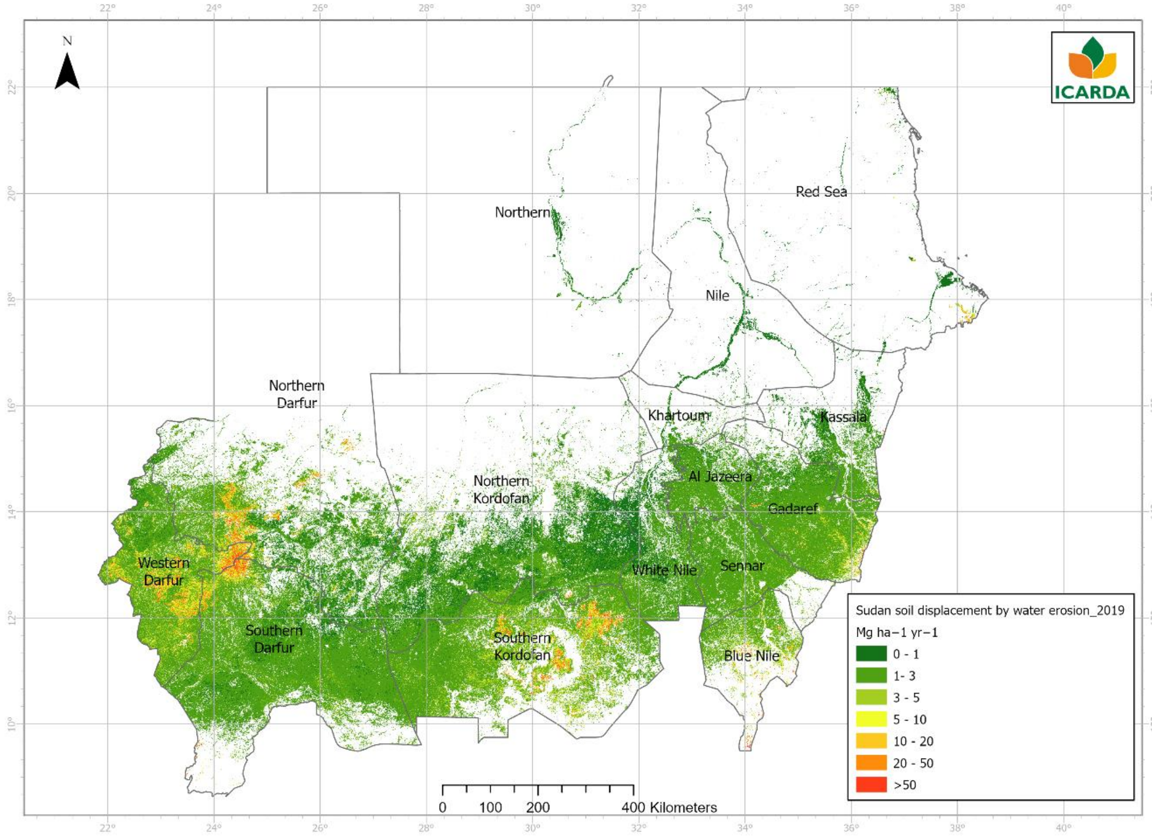



*Figure 12. Soil Erosion map of Sudan (Data source: ESDAC).*

*Table 3. Shows the area in ha of the different soil erosion classes in (Mg ha−1 yr−1) for each state of Sudan.*

| State | 0_1 | 1_3 | 3_5 | 5_10 | 10_20 | 20_50 | >50 |
|---|---|---|---|---|---|---|---|
| Al Jazeera | 171304.25 | 1662721.51 | 24594.70 | 1650.23 | 32.26 | 19.85 | 0.00 |
| Blue Nile | 0.00 | 948418.20 | 468262.05 | 83906.35 | 12706.80 | 13822.26 | 21281.82 |
| Khartoum | 77440.66 | 199878.12 | 2379.81 | 234.51 | 55.83 | 91.82 | 7.44 |
| Northern | 196349.35 | 37607.97 | 1900.87 | 565.79 | 53.35 | 12.41 | 0.00 |
| Northern Darfur | 1015235.32 | 4029895.79 | 480936.60 | 199643.61 | 129166.20 | 135743.56 | 38864.88 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nile | 311066.69 | 45333.05 | 282.90 | 33.50 | 7.44 | 0.00 | 0.00 |
| Sennar | 36633.96 | 2777639.67 | 160741.51 | 10137.15 | 1297.85 | 1665.12 | 1013.72 |
| Southern Darfur | 848772.59 | 8090871.81 | 630302.66 | 128841.11 | 64402.57 | 72576.81 | 37343.69 |
| Western Darfur | 101642.03 | 3088353.97 | 1190006.30 | 415506.67 | 194396.36 | 184836.17 | 58126.71 |
| White Nile | 809859.32 | 2058932.84 | 41388.62 | 1826.42 | 181.15 | 151.37 | 33.50 |
| Southern Kordofan | 109466.37 | 5687309.25 | 1834953.86 | 327427.58 | 109226.90 | 128131.39 | 78224.83 |
| Red Sea | 231727.64 | 28336.88 | 7803.25 | 12617.47 | 13354.49 | 10355.53 | 950.44 |
| Kassala | 466424.46 | 1114599.28 | 16786.48 | 4356.37 | 1895.91 | 1490.17 | 400.77 |
| Northern Kordofan | 2808102.00 | 5231587.73 | 174653.11 | 22806.73 | 6087.26 | 5846.54 | 3635.48 |
| Gadaref | 208984.19 | 3657689.78 | 436134.60 | 82921.17 | 19444.23 | 15337.25 | 5332.86 |

# 3. Soil-water resources

## 3.1. Groundwater recharge

The groundwater recharge map for Egypt was developed using data from the Groundwater Resources Map of the Worldwide Hydrogeological Mapping and Assessment Program (WHYMAP), which incorporates all relevant published data available to date. This map delineates the various characteristics of groundwater resources by using a color-coded system:

- Blue indicates large and relatively uniform groundwater basins, including aquifers and aquifer systems often found in extensive sedimentary basins, likely to provide favorable conditions for groundwater extraction
- Green signifies areas with complex hydrogeological structures characterized by highly productive aquifers within heterogeneous and folded terrains, situated close to regions lacking significant aquifers
- Brown represents areas with constrained groundwater resources, typically due to the presence of shallow aquifers.

In Sudan, certain areas are identified as having limited groundwater resources with a recharge rate ranging from medium to very low, less than 100 mm per year. Notably, in the Nile state and around 60 percent of the Al Jazeera state, there are large uniform groundwater basins with low recharge rates varying from 2 to 20 mm per year. The majority of the White Nile state encompasses large uniform groundwater basins with medium recharge rates between 20 to 100 mm per year, while most areas in the Northern state are characterized by large uniform groundwater basins with very low recharge rates below 2 mm per year. These groundwater characteristics and recharge rates are illustrated in the Groundwater Recharge Map shown in Figure 13.

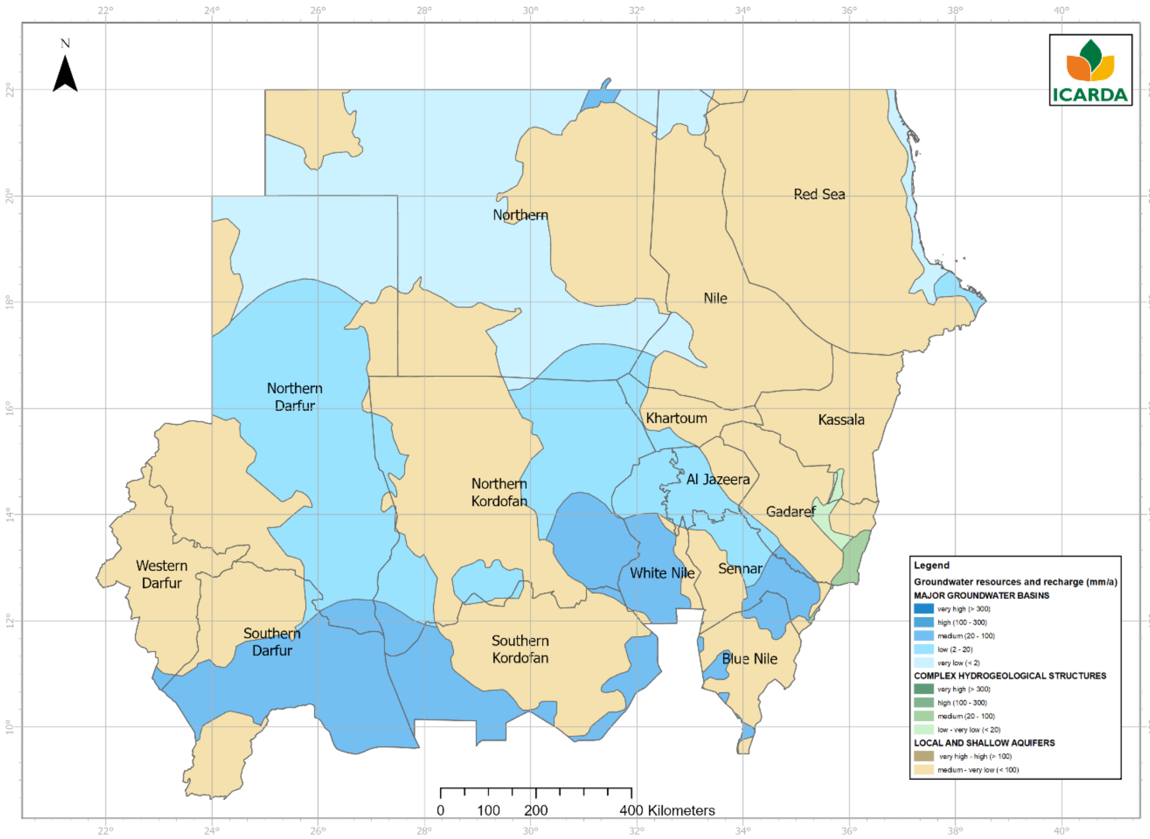



*Figure 13. Groundwater recharge in Sudan (Data source: WHYMAP).*

## 3.2. Dams

The dataset for Sudan's dams was sourced from the Global Reservoirs and Dams (GRanD) version 1.01, developed by Lehner et al. (2011). This dataset includes information on major dams such as the Roseires Dam, with a capacity of 4,483 million cubic meters, the Sennar Dam, holding 4,482 million cubic meters, the Khashm el Girba Dam, with 4,481 million cubic meters, and the Jebel Aulia Dam, containing 4,480 million cubic meters. These significant water structures in Sudan are highlighted in Figure 14.

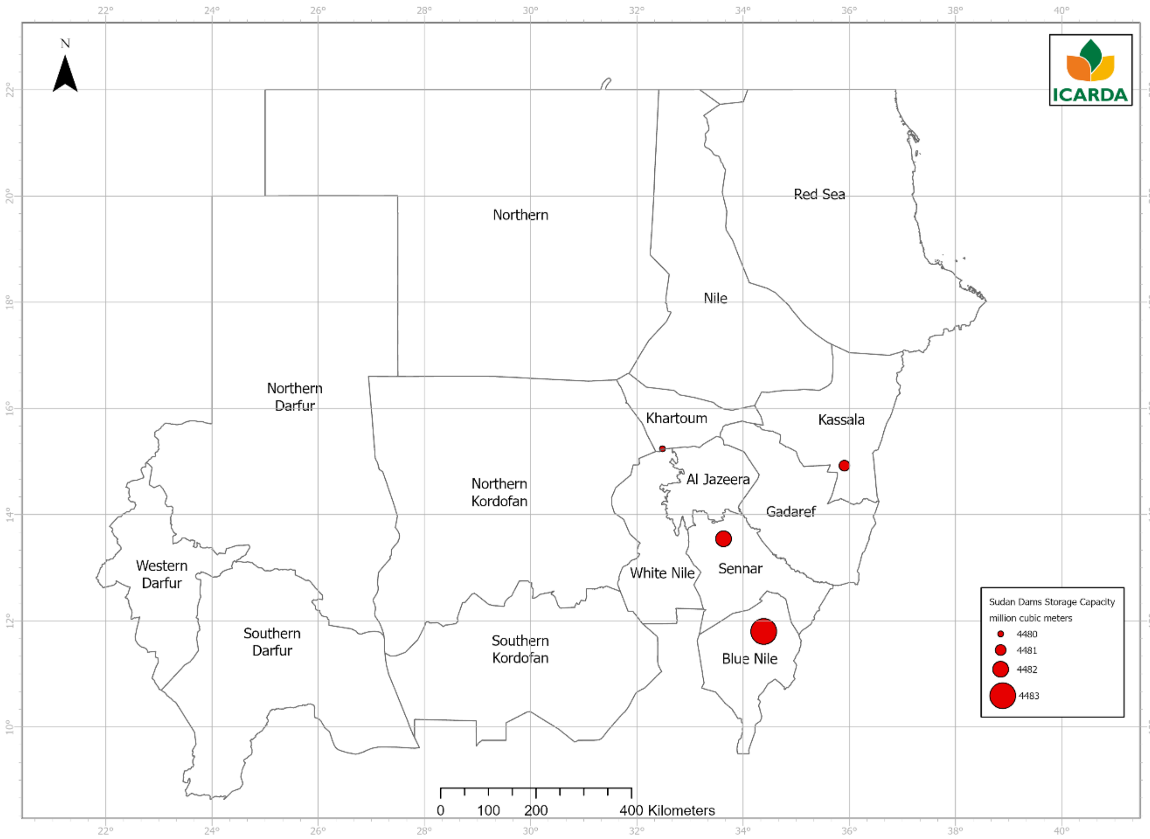



*Figure 14. Existing dams in Sudan (Data source: Lehner et al., 2011, Global Reservoirs and Dams).*

# 4. Land use land cover, hot-spots, and land use

## 4.1. Normalized difference vegetation index

Winter crops like wheat exhibit their peak vegetation from January to March. The seasonal average NDVI (Normalized Difference Vegetation Index), illustrated in Figure 15, was derived from the MODIS MOD13Q1 V6 NDVI data. MODIS NDVI calculations are based on atmospherically corrected bi-directional surface reflectance, which excludes water bodies, clouds, heavy aerosols, and cloud shadows. For Sudan, the seasonal NDVI values fluctuate between 0 and 0.8. During the peak vegetation period from January to March, as shown in Figure 15, NDVI values in certain areas span from 0.5 to 0.8. Notably, the Al Jazeera state encompasses the largest portion of land with NDVI values within this range compared to other Sudanese states.

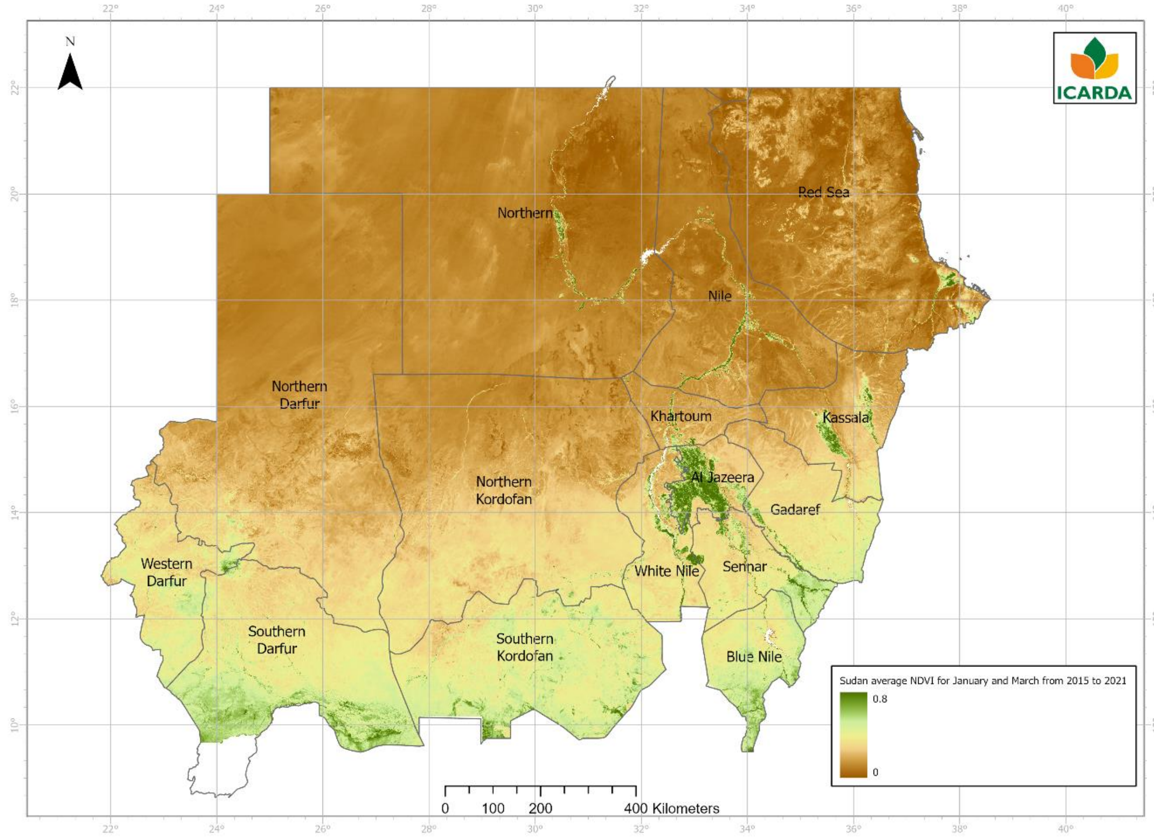



*Figure 15. NDVI in Sudan from November to March from 2015-2021.*

## 4.2. Hotspot and suitability mapping

Threshold values for various biophysical traits relevant to wheat cultivation in Sudan were established based on the expertise of agronomists specializing in this domain. These values were utilized to identify hot spot constraints for wheat cultivation and to assess the suitability of different areas in Sudan for this purpose, as detailed in Table 4 and Table 5, respectively.

*Table 4. Threshold values of biophysical parameters for mapping hotspot constraints for wheat cultivation in Sudan.*

| SN | Biophysical characteristics | Hotspot |
|---|---|---|
| 1 | Annual average rainfall (mm) | <50 |
| 2 | Groundwater recharge (mm/ha) | <20 |
| 3 | Annual minimum temperature change ($^0$C) | >0.5 |
| 4 | Slope (%) | >20 |
| 5 | Maximum temperature ($^0$C) | >40 |
| 6 | Minimum temperature ($^0$C) | <10 |
| 7 | NDVI January to March | <0.3 |
| 8 | Annual precipitation changes (mm) | <5 |
| 9 | Soil displacement by erosion (Mg/ha) | >5 |
| 10 | Soil organic carbon in 0-30 cm (g/kg) | <20 |
| 11 | Annual temperature change ($^0$C) | >0.5 |

| | | |
|---|---|---|
| 12 | Soil salinity | >50 (>5 dS/m) |

*Table 5. Threshold values of biophysical parameters for suitability mapping for wheat in Sudan.*

| SN | Biophysical characteristics | Suitability |
|---|---|---|
| 1 | Annual average rainfall (mm) | >200 |
| 2 | Groundwater recharge (mm/ha) | >100 |
| 3 | Annual minimum temperature change ($^0$C) | <0.5 |
| 4 | Slope (%) | <20 |
| 5 | Maximum temperature ($^0$C) | <40 |
| 6 | Minimum temperature ($^0$C) | >10 |
| 7 | NDVI January to March | >0.5 |
| 8 | Annual precipitation changes (mm) | >5 |
| 9 | Soil displacement by erosion (Mg/ha) | <5 |
| 10 | Soil organic carbon in 0-30 cm (g/kg) | >30 |
| 11 | Annual temperature change ($^0$C) | <0.5 |
| 12 | Soil salinity | <50 (<5 dS/m) |

### 4.2.1. Suitability Mapping

Twelve raster datasets representing key biophysical factors for wheat cultivation were modified according to the guidelines in Table 5 for integration into the suitability modeling tool within the ArcGIS Pro platform, facilitating the creation of a suitability map for Sudan (Fig. 16). The suitability scale ranged from 1, indicating no or very low suitability, to 10, signifying high suitability, without applying any weighting to ensure equal consideration for all criteria.

The modification process was structured as follows: a transformation table (Table 6) detailed how values across a spectrum of classes would be adjusted, listing the Class, Start, End, and Suitability values. The Start and End values demarcate the range for each class, with a corresponding suitability value dictating the conversion of these ranges into the suitability scale for each criterion.

For data involving specific categories, such as groundwater recharge, another transformation table (Table 7) was established to guide the conversion process. This table outlined the Class, Category, and Suitability values, where the Category determines the class's assigned suitability value. This suitability value then elucidates the method by which the category's data is adapted to fit the suitability scale for the respective criterion.

*Table 6. The transformation table of the biophysical characteristics for suitability mapping of data that has a range of classes.*

| Slope | | | |
|---|---|---|---|
| Class | Start value | End value | Suitability |
| 1 | 0 | 20 | 10 |
| 2 | 20 | 52.77 | 1 |
| Soil displacement by erosion | | | |
| 1 | 0 | 5 | 10 |

| | | | |
|---|---|---|---|
| 2 | 5 | 200 | 3 |
| Soil Organic carbon | | | |
| 1 | 1.9 | 30 | 5 |
| 2 | 30 | 71.3 | 10 |
| Minimum temperature | | | |
| 1 | 7.31 | 10 | 1 |
| 2 | 10 | 25.37 | 10 |
| Precipitation | | | |
| 1 | 0 | 200 | 5 |
| 2 | 200 | 908.28 | 10 |
| NDVI | | | |
| 1 | 0 | 0.5 | 5 |
| 2 | 0.5 | 0.73 | 10 |
| Minimum temperature changes | | | |
| 1 | 0 | 0.5 | 5 |
| 2 | 0.5 | 0.73 | 10 |
| 3 | 0.5 | 1.35 | 7 |
| Maximum temperature changes | | | |
| 1 | -0.23 | 0 | 10 |
| 2 | 0 | 0.5 | 5 |
| 3 | 0.5 | 1.3 | 3 |
| Precipitation changes | | | |
| 1 | -21.4 | 5 | 5 |
| 2 | 5 | 6.08 | 10 |
| Soil salinity | | | |
| 1 | 0 | 5 | 10 |
| 2 | 5 | 19.79 | 3 |

*Table 7. The transformation table of the biophysical characteristics for suitability mapping of data with unique categories.*

| GWR Class | category | Suitability |
|---|---|---|
| 1 | 11 | 2 |
| 2 | 12 | 2 |
| 3 | 13 | 10 |
| 4 | 22 | 2 |
| 5 | 23 | 10 |
| 6 | 33 | 2 |

The final suitability map (Fig 16) reveals that the region's most suitable for wheat cultivation in Sudan, highlighted in green, are located in the southern part of the country, specifically within the White Nile, Southern Kordofan, and Southern Darfur states.

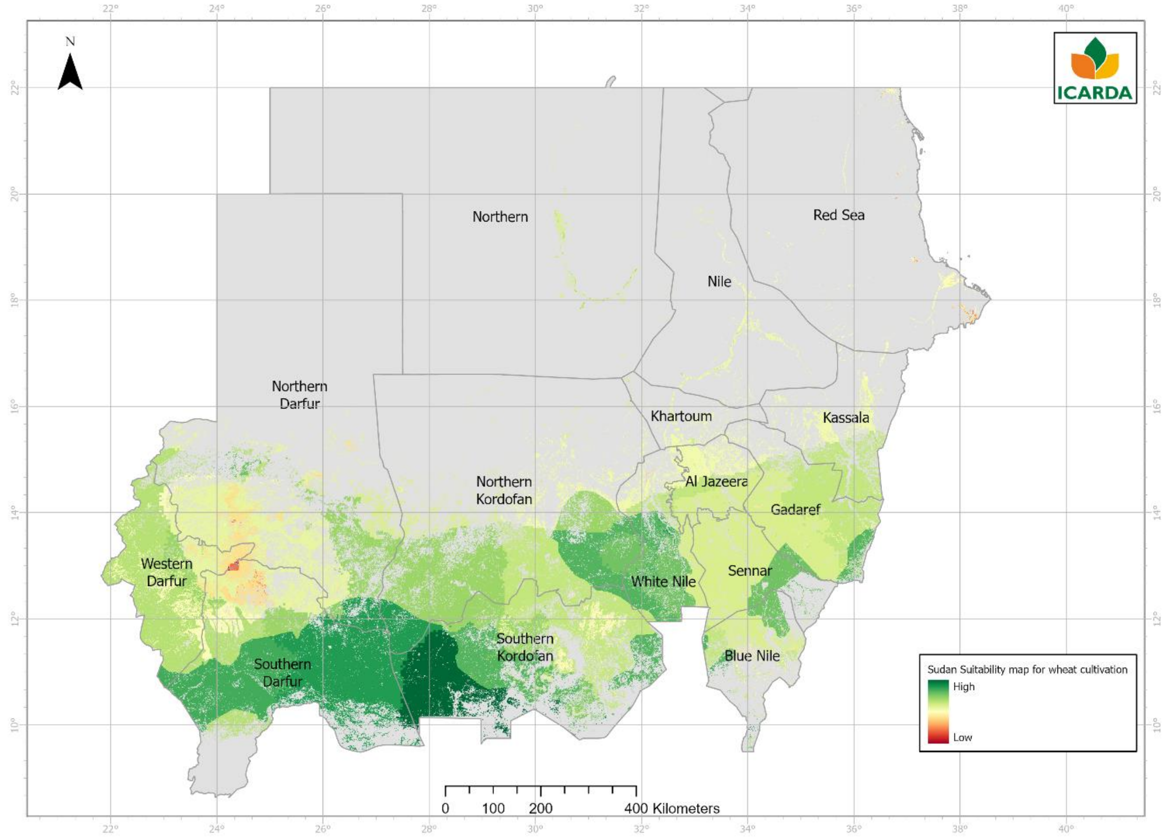



*Figure 16. Suitability for wheat cultivation in Sudan.*

## 4.2.2. Hotspot Mapping

Utilizing the threshold values outlined in Table 4 for biophysical factors relevant to identifying hotspot constraints for wheat cultivation, each biophysical raster dataset was categorized into two classes using the IF Condition in the ArcGIS Pro platform. In this classification, a value of 1 indicates the data meets the specified range (true condition), and a value of 0 indicates it does not (false condition). Notably, no maximum temperature values exceeded 40°C in Sudan, leading to their exclusion from the hotspot analysis. The cell statistics tool, part of the spatial analyst toolkit in ArcGIS Pro, was employed to compile the hotspot layer by aggregating the eleven adjusted datasets. The resultant hotspot map (Fig 17) illustrates that Sudan's southern states, such as Southern Kordofan and Southern Darfur, display lower constraint values in green, indicating favourable conditions for wheat cultivation. Conversely, the northern regions, including the Red Sea area and parts of Northern Darfur and Northern states, are marked in red, signifying areas with greater constraints on wheat cultivation.

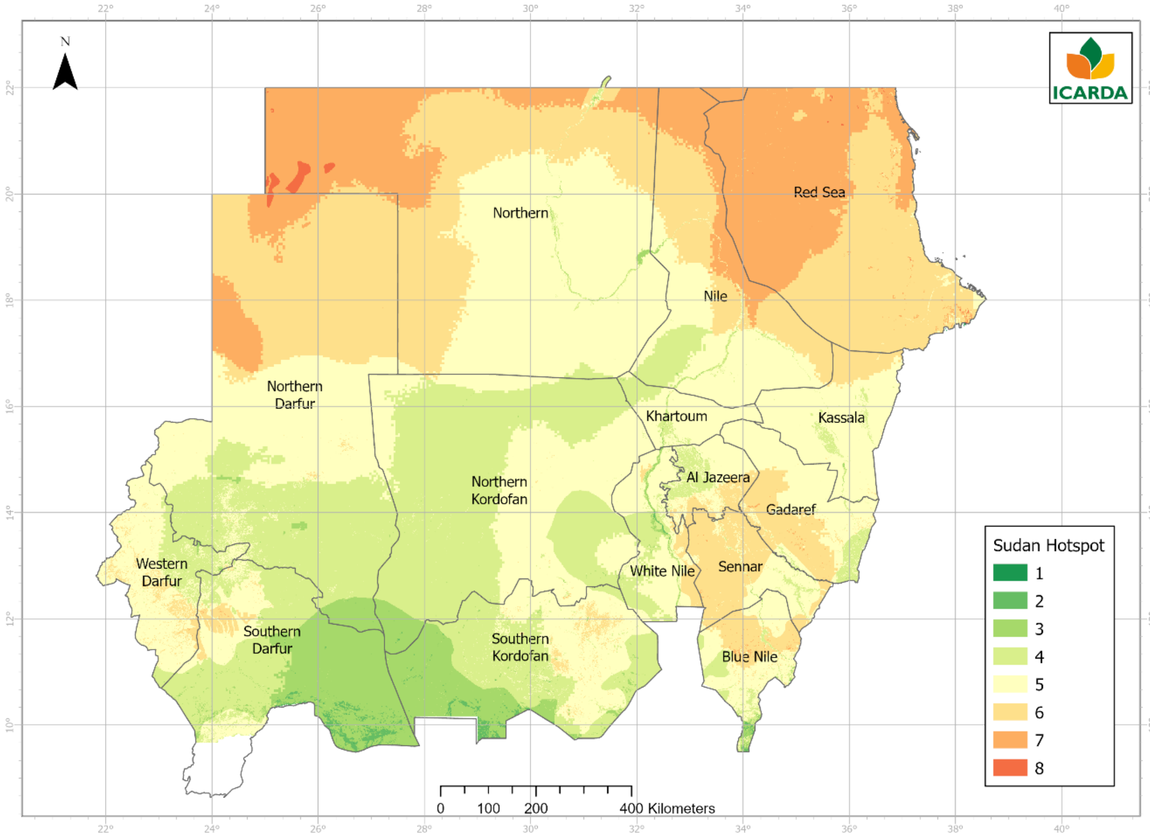



*Figure 17. Map of hotspot constraints for wheat cultivation in Sudan.*

## Acknowledgments

This report is the output from OneCGIAR Regional Initiative F2R CWANA Work Package 3.

## References

African Development Bank Group (2023). Sudan- Emergency Wheat Production Project (SEWPP) – Project Appraisal Report.

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, *5*(1), 1–12.

Borrelli P., Robinson D.A., Fleischer L.R., Lugato E., Ballabio C., Alewell C., Meusburger K., Modugno, S., Schutt, B. Ferro, V. Bagarello, V. Van Oost, K., Montanarella, L., Panagos P. 2017. An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications,* **8 (1)**: art. no. 2013

Didan, K. *MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006*. 2015, distributed by NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/MODIS/MOD13Q1.006. Accessed 2022-12-26.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., & Roth, L. (2007). The shuttle radar topography mission. *Reviews of Geophysics*, *45*(2).

Fischer, G., Nachtergaele, F., Prieler, S., van Velthuizen, H. T., Verelst, L., & Wiberg, D. (2008). Global agro-ecological zones assessment for agriculture (GAEZ 2008). *IIASA, Laxenburg, Austria and FAO, Rome, Italy*, *10*.

Lehner, B., Liermann, C. R., & Revenga, C. (2011). Vö rö smarty C, Fekete B, Crouzet P, Dö ll P, Endejan M, Frenken K, Magome J, et al.: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front Ecol Environ*, *9*, 494–502.