International Journal of Engineering and Geosciences
https://dergipark.org.tr/en/pub/ijeg
e-ISSN 2548-0960

Mapping the structural vulnerability to drought in Morocco

Noureddine Bijaber *[1], **Atmane Rochdi** [2], **Mohammed Yessef** [3], **Houda El Yacoubi** [2]

[1] Royal Centre for Remote Sensing, Rabat, Morocco, nbijaber@yahoo.fr
[2] Ibn Tofail University, Research Unit of Agro-physiology, Biotechnology and Environment; Laboratory of Natural Resources and Sustainable Development; Kenitra, Morocco, atmane.rochdi@uit.ac.ma, houda.elyacoubi@uit.ac.ma
[3] Institut Agronomique et Vétérinaire Hassan II, Rabat, Morocco, y_toufik2006@yahoo.fr

Cite this study: Bijaber, N., Rochdi, A. Yessef, M., & El Yacoubi, H. (2024). Mapping the structural vulnerability to drought in Morocco. International Journal of Engineering and Geosciences, 9 (2), 264-280

https://doi.org/10.26833/ijeg.1404507

Keywords
Drought
Structural vulnerability
Remote sensing

Research Article

Received: 13.12.2023
Revised: 01.03.2024
Accepted: 24.03.2024
Published: 25.07.2024

Abstract

Because of its recurrence and the durability of its effects, drought in Morocco has become a structural component of the Moroccan climate. It is a real threat to the agricultural sector, which represents nearly 20% of the Moroccan economy. The spatiotemporal variability of this phenomenon makes drought risk management more complex. The current study seeks to map the structural vulnerability to drought in Morocco by using remote sensing techniques to characterize its sensitivity to drought. In this premise, we utilized a weighted combination of soil classes, land cover and socio-economic data with seasonal drought monitoring through a composite index generated monthly over the past twenty years. The generated map shows dominance of areas with high and very high vulnerability risk to drought over respectively 38.5% and 14.4% of the country and this concerns both agricultural and non-agricultural zones. The map also indicates that 36.5% of Morocco presents a medium vulnerability to drought and only 10.6% of the national territory is considered non-vulnerable to drought. This map can be used as a planning tool to support natural resources management and mitigate drought impacts.

1. Introduction

In arid and semi-arid areas, the degradation of natural resources and water scarcity due to recurrent droughts reduce economic and biological productivity and contribute to the ecological deterioration and fragility [1]. Such losses amplify the vulnerability of the agricultural areas to these extreme climate hazards [2].

Due to its arid and semi-arid geographic situation, Morocco faces different climate change induced challenges such as aridity, spatiotemporal scarcity and irregularity of water resources, recurrent droughts, desertification, etc. The climate setting of the country has a considerable impact on agricultural production, which is an important contributor to the national economy and it is strongly dependent on the amount and spatio-temporal distribution of rainfall. During last few years, drought in Morocco resulted in serious losses in agricultural and livestock production and increased the forest fires incidents and the shortage of drinking water storage [3].

Vulnerability may exist because of high exposure to the drought hazard, and it can be either cyclical or structural. The cyclical vulnerability to drought is defined as the degree of loss in general productivity due to rainfall scarcity in a given limited period of time (month, season and year) [2]. For this type of vulnerability, the impact can be reduced, on one hand, by the first coming rains and on the other hand, by the short-term decisions taken by the government (creation of seasonal jobs in rural areas, mobilization of funds, drought mitigation activities, etc.). The structural vulnerability to drought concerns all the components of the hydrological cycle and all the fields of water use including meteorology, hydrology, agronomy, forestry and socio-economy. This type of vulnerability has a long-term dimension and its assessment can be used as a benchmark in drought mitigation plans by classifying areas according to their level of sensitivity to drought.

It is obvious that the structural and cyclical concepts of vulnerability interact: the first one is described as structural vulnerability to drought because there is a repetitive cyclical vulnerability whose impacts on natural resources are becoming increasingly devastating [2]. In addition, early warning must take into account all the static and dynamic factors that characterize the sensitivity of any ecosystem.

The main purpose of this work is to develop a methodology for mapping structural vulnerability to drought in Morocco. Such a map can be used as a planning tool to support managers and decision-makers in limiting drought impacts and reducing vulnerability before the potential of damage is realized. The first part of this paper presents generalities about vulnerability to drought followed by a detailed description of the methodology adopted for the structural vulnerability mapping (data used, derived parameters, combined indicators and weighting).

2. Generalities on vulnerability to drought

The concept of vulnerability is common to all operational early warning systems. Vulnerability is an overall indicator that measures the capability of a region (or of a group) to resist, cope with and to recover from the impact of a negative event [2]. It takes into account the factors (societal, physical and natural) that contribute to and influence a disaster risk, the probability of occurrence of such event, and the level of exposure to risk of different groups, areas and/or sectors.

Vulnerability is not a measurable feature of a system, such as temperature, precipitation or agricultural production. It is a concept that reflects the complex interaction of several factors that determine a system's sensitivity to the effects of climate change [4]. Vulnerability to drought is the characteristic of an area for which there is a high probability that the drought risk will turn into concrete events such as crop failures, livestock losses, famine, etc. It describes the fragility of the system exposed to an extreme climatic event (drought) and it is related to the intensity and duration of this extreme event.

In the context of drought, there are two main types of vulnerability to take into consideration in monitoring and warning systems. The first one is the seasonal vulnerability, which is based on the modeling of agro-climatic parameters combined with remote sensing data and crop growth modeling for the assessment of the current season based on yield estimates [5,6]. The second type is the structural vulnerability, which refers to the characteristics of a social group or sector in terms of its capacity to anticipate, cope with, and to recover from drought [2].

More specifically, vulnerability to agro-climatic drought can be defined as the "characteristic of an entity (zone or human group) for which there is a high probability that the agro-climatic risk will turn into a concrete event" [7]. The term *"human group"* refers to groups that are not necessarily linked to a specific territory, such as pastoralists or farmers (producers of a specific crop). The term *"concrete event"* refers, for example, to a reduction in the value of the yields which controls the farmers' income [2].

According to the National Drought Mitigation Center [7], the main components of the disaster management cycle are preparedness, mitigation, prediction and early warning activities. Risk management emphasizes these components initiated before drought with the goal of reducing the impacts associated with subsequent events. For the cycle of drought risk management, the preparedness is the most important phase, and it is the one on which efforts must focus. It includes all the structural decisions and activities to take in case of drought. It concerns the implementation of tools and processes as well as methodologies to develop drought plans and appropriate responses in anticipation to drought occurrence.

Mapping structural vulnerability to drought requires the definition and preparation of relevant and easily accessible indicators and indices representing the entire studied territory [8]. The vulnerability assessment maps contribute to better targeting areas prone to or affected by the disaster. By understanding the causes of vulnerability to drought, managers can design proactive measures to decrease the potential impacts of drought and increase the adaptation capacity of a community [9].

3. Materials and methods

Mapping the structural vulnerability to drought is a complex and challenging task because the phenomenon itself is complex and difficult to assess. Different parameters and factors (physical, social, economic and environmental factors) [10,11] are involved in the study of drought vulnerability and their use may depend on data availability. Despite these limitations and the complexity of the task, we tried to produce a structural vulnerability map for Morocco based on the existing and operational data.

To this purpose, we adopted the methodology of drought vulnerability assessment developed in the Vulnerability Sourcebook, Concept and Guidelines for standardized vulnerability assessments [12]. According to these guidelines, vulnerability is a function of three major drivers, including exposure, sensitivity and adaptive capacity. The combination of exposure and sensitivity determines the potential impact of the vulnerability on people, economic sectors and socio-ecological systems.

3.1. Datasets

Various datasets were gathered and integrated from different sources and with different characteristics by using geographic information systems (GIS) and programming technics. The present study is based on a combination of four groups of datasets, namely: the monthly-generated drought composite index over the last twenty years, the distribution of soil classes, the land cover map and the recent global poverty index resulting from the general population census of Morocco.

3.1.1. Periodic drought index

The Royal Centre for Remote Sensing (CRTS) has recently developed a gridded composite drought indicator (CDI) based on a combination of different parameters derived from various satellite-based earth observation data at the national scale. Row products are periodically downloaded and processed to generate a monthly basis CDI over Morocco at a 5km resolution (which is the precipitation estimates resolution). This composite index is the result of a study that has been done in the framework of a global project (Land Data Assimilation System, LDAS) financed by the World Bank with the technical support of the American space agency (NASA) and the National Drought Mitigation Centre of the University of Nebraska. The main purpose of the composite approach was to leverage the relevant strengths of each parameter and provide a single index that was representative of different drought severity classes at the national scale [13,14].

The developed CDI tool incorporates information related to four different parameters and indices derived from earth observation data [15]. These parameters are:

- Standardized Precipitation Index (SPI) from satellite-based rainfall data. The Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) represents satellite estimates corrected by integration of rainfall data from weather stations on the ground. These data are available from 1981 to present at 5 km spatial resolution [16]. We used the available CHIRPS archived data set to calculate the standardized precipitation index (SPI) over a two-month period [17,18]. The SPI-2 provides comparison of the precipitation over 2-month specific period with the historical average precipitation of the same 2-month period dating back to 1981.

- Normalized Difference Vegetation Index (NDVI) anomalies. The 10-day maximum-value composite NDVI anomalies generated from MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imager Radiometer Suite) data were periodically downloaded from Famine Early Warning Systems Network (FEWSNET) portal since 2001 [19]. This parameter represents the anomalies of the current vegetation conditions compared to the historical conditions for the same period.

- Land Surface Temperature (LST) based Soil Moisture Proxy anomalies. Two daily satellite-based observations were derived from MODIS Terra sensor: day and night land surface temperature (LST) to calculate a monthly composite diurnal changes in LST. The generated MODIS day-night LST anomalies were used as indicators of soil moisture. Indeed, relative soil moisture can be estimated using LST observations in the thermal infrared region [20]. According to Hain et al., [20] and Wan et al., [21,22], the evolution of LST in the morning hours is strongly dependent on current soil moisture conditions, as wet soil will heat up more slowly and dry soil will heat up more rapidly [20-22].

- Evapotranspiration anomalies (ETA). The ETA gridded data products are open-access and obtained from FEWSNET platform. This parameter is calculated by using the Operational Simplified Surface Energy Balance (SSEBop) model, which is a simplified energy balance method incorporating thermal data from MODIS since 2003 [23].

These four input data sets cover the Moroccan territory with different spatial resolutions (5km for SPI from CHIRPS, 250m for NDVI, 1km for ETA and LST from MODIS). In order to have a uniform spatial resolution for the CDI, all the indices were sampled to a 5km spatial resolution consisting of 25,589 grid cells in total over Morocco [13].

The CDI is calculated monthly by using the weighted arithmetic aggregation method and by assigning the highest weight to the rainfall-based parameter (40%). Indeed, the 2-month SPI has a strong relationship with drought onset, duration and intensity according to a retrospective comparison between the CDI input parameter maps and real drought episodes from the past (using ground truth data: precipitation measurements and cereal productions). The other three indices (NDVIa, ETA and LST) were considered factors resulting from the impact of rainfall deficit and were equally weighted (20% each). The final CDI map presents four drought intensity classes [24] as described in Table 1.

Table 1. Drought intensity categories.

Drought classes	Class names	CDI Percentiles
D0	No drought	> 20
D1	Moderate	10 to 20
D2	Severe	5 to 10
D3	Extreme	2 to 5
D4	Exceptional	< 2

The composite drought index maps are generated at a monthly time scale with the spatial resolution of 5km since January 2003 during the agricultural seasons (October to April). The analysis of this historical CDI database over the past 20 years has enabled us to study and to assess the severity and duration of the occurred drought events. Areas with the highest drought frequency were the most vulnerable and those with the lowest frequency were less vulnerable [25-27]. The approach of drought frequency analysis was based on the identification of areas where the different drought intensity classes occurred both during the first parts of the growing seasons and also during the most sensitive parts of the growing periods. This represented the first component of the vulnerability, which is 'Exposure'.

3.1.2. Soil data

Soils are threatened by various forms of degradation (erosion, biological and physicochemical degradation, salinization, pollution) that lead to a decrease in soil fertility and productivity [28]. In case of rainfall deficit, water reserves in the superficial layers of the soil become insufficient during the growing season. This "edaphic" drought is the classic drought in agriculture caused by the scarcity and/or bad distribution of rainfall during the agricultural season, and is highly dependent on soil proprieties (composition, thickness and depth, texture, bio-physicochemical characteristics, etc.).

Soil maps are especially useful when it comes to understanding how different soils may respond to droughts. For example, sandy soils are more prone to drying out quickly and deeply during a drought due to their low water retention capabilities. Meanwhile, clay soils can retain moisture for longer periods and avoid such severe effects from droughts. Gridded information about global soil categories regarding drought sensitivity levels is a fundamental step in the study of structural vulnerability to drought. Therefore, we used the map published by the International Soil Reference Information Centre (ISRIC) called SoilGrids [29] that provides global information on standard soil properties at different depths (organic carbon, cation exchange capacity, pH, etc.) and on the distribution of soil classes based on the international soil classification systems. The most recent version of SoilGrids is available at 250m spatial resolution [29].

3.1.3. Land cover data

Land cover is an important variable for understanding the vulnerability of an area to drought. It describes the spatial distribution of the main land surface classes (irrigated and non-irrigated crops' cultivated areas, forests, rangelands, water bodies, etc.) and allows their classification based on their sensitivity to drought. For example, areas with grasslands and non-irrigated annual crops will suffer more quickly compared to those with trees and perennial plants that can retain moisture better. It is also important to take into account changes in land use such as irrigated areas or urban development that may increase the fragility of a system during prolonged periods of drought [30].

In the present study, we generated a land cover map at national scale by classifying multi-temporal remotely sensed data sets (Sentinel2 at 10 m resolution). The approach was fully automatic using high-resolution optical image time series acquired between September 2020 and December 2021 (at least two images per month), and classified using an automatic processing chain [31]. Once all the time series tiles were downloaded, the preprocessing phase comprised the following steps:

(1) Image processing with their validity masks (clouds, cloud shadow, saturation, etc.),

(2) Temporal gap filing and resampling,

(3) Reference data preparation and split into training and validation subsets,

(4) Features extraction from each dataset (NDVI, NDWI and the brightness) and their concatenation to produce a mosaic of the downloaded tiles.

The adopted classification method required the collection of data for training and validation. The advantage of this automatic approach was to rely on existing databases to build the reference data sets needed for supervised classification and the subsequent validation of the results.

The land cover map resulting from Sentinel-2 images classification for the year 2020-2021 had a total accuracy of 85.72% and a Kappa coefficient equal to 0.84. This accuracy level was acceptable to use for the study of the structural vulnerability in Morocco because all the generated classes were merged into four main classes in term of their vulnerability to drought [12,32]. However, since the approach was fully automatic and based on open existing data, the land cover map will be updated at a regular periodicity in the future.

Both soil and land cover data described above present the second component of the vulnerability, which is Sensitivity that determines the degree to which the ecosystem is affected by the impacts of the first component of vulnerability (Exposure).

3.1.4. Socio-economic data

Structural vulnerability to drought is historically and closely linked to the population poverty, which is a main component of the socio-economic vulnerability. When an area experiences a drought, those living in poverty have little to no access to basic necessities, such as food and water. This part of population is particularly vulnerable to external shocks, including those caused by natural disasters. They have a lower capacity to deal with shocks than non-poor households, due to lower access to savings, borrowing, or social protection [33]. As a result, people living in poverty during periods of drought conditions become particularly vulnerable making them more susceptible to long-term effects such as lowered immunity levels and further health problems.

On the other hand, natural disasters are a key factor for pushing vulnerable households into poverty and keeping households poor. Exposure to natural hazards may reduce incentives to invest and save, since the possibility of losing production and livestock due to a drought, makes these investments less attractive [33]. This vulnerability is more accentuated in rural areas where people are in general engaged in agricultural activities rain dependent.

The impacts of drought across societies, economies and ecosystems are significant and difficult to quantify from an economic perspective [34]. Nowadays, many indices and indicators exist at international level to monitor the human quality of life for each country and describe the socio-economic vulnerability to drought. These vulnerability indices reflect the capacity of a population to anticipate, resist, adapt to and recover from the impact of drought events [12].

In Morocco, the main source of information on socio-economic aspects is the high authority in charge of population planning (Haut-Commissariat au Plan, HCP) that owns all the statistics about the Moroccan population. Among the available indices presenting the degree of social fragility to drought, we selected the global poverty index that incorporated both monetary and multidimensional poverty. This type of poverty described the rate of population with little access to essential services like education, health and living conditions compared to the national poverty line. The available data exist in tabular format resulting from the general population census of Morocco conducted in 2014 [35]. In the present study, we retrieved and spatialized the global poverty index available at communal scale and reclassified it into levels of socio-economic vulnerability. The integration of this parameter into the geodatabase process is detailed below (§3.2.4. Adaptive Capacity).

3.2. Methodology

The approach developed in this study was based on the various parameters and factors described above and it was adopted from the global methodology of drought vulnerability assessment combining the main drivers, including exposure, sensitivity and adaptive capacity [12]. Figure 1 summarizes the data used and the main steps for structural vulnerability mapping.

The framework presents the selection of indicators and the weighted combination of parameters to generate the vulnerability classes at national scale [36]. The methods for extracting and combining the different factors for drought vulnerability mapping are described.

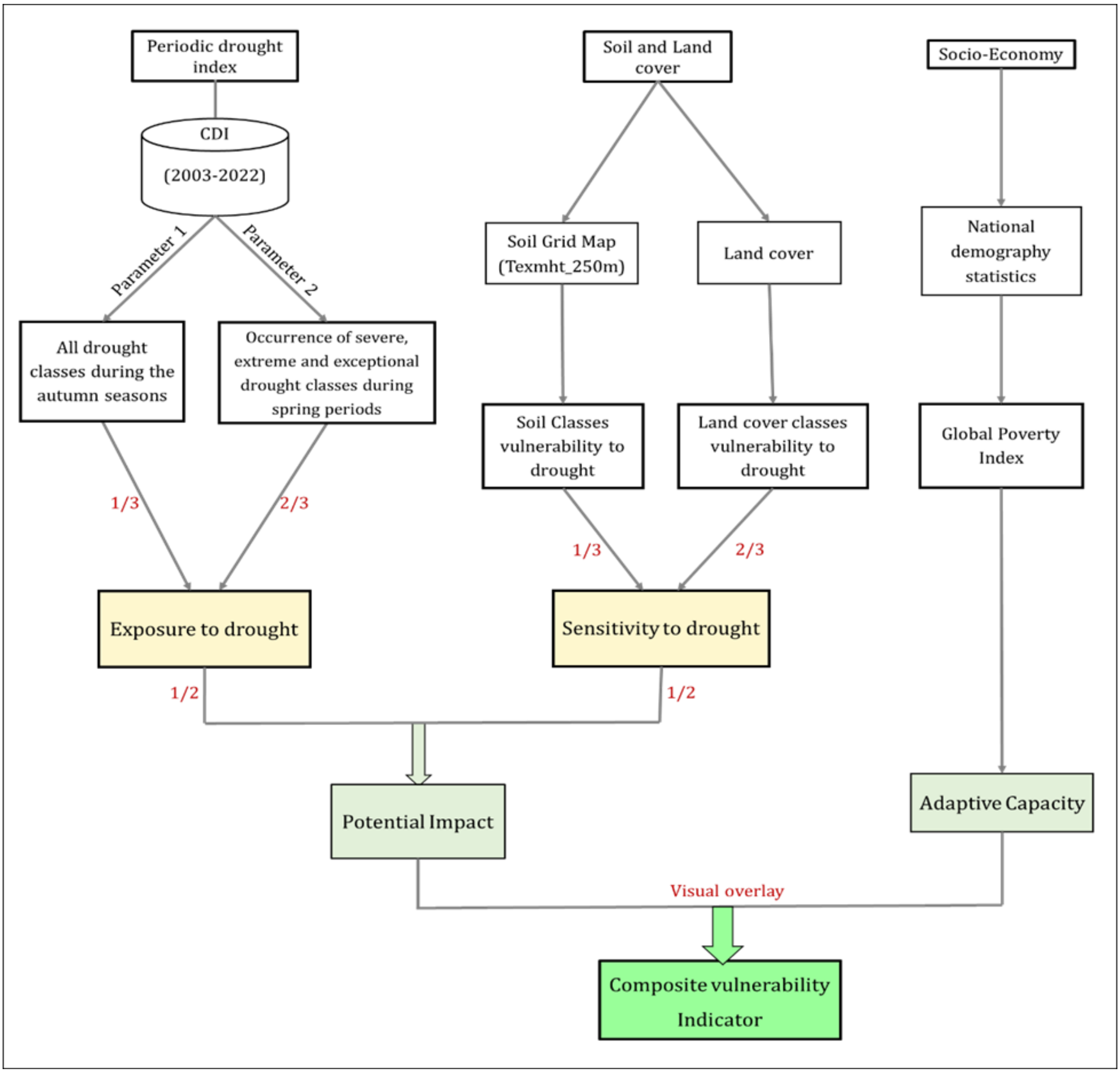

Figure 1. Methodology for mapping the structural vulnerability to drought.

3.2.1. Mapping the exposure to drought

This first component of the vulnerability is related to climate parameters through seasonal drought frequencies. In the periodic CDI composition, the climate parameters are represented by precipitation index (SPI_2), land surface temperature (LST) as well as evapotranspiration. The vegetation index (NDVIa, weighted 20%) reflects the results of the impact of climate drivers on vegetation status. In Morocco, the agricultural season for cereals is divided in three main periods: the first one concerns soil preparation, seeding and germination from September to December, the second period covers crops development from January to April and the third one is the harvest period from May to July depending on regions. During the cereal reproductive development periods (spring), there is a strong correlation between the climate parameters and the yields [37].

In the present study, two principal exposure factors were selected from the CDI database generated over the last twenty years [38]. The first one (P1 parameter) is the occurrence of all drought classes recorded in the autumn seasons, and the second parameter (P2) is the occurrence of severe, extreme and exceptional drought classes observed during the spring seasons (January to April of each year).

In other words, the approach consists in calculating for each pixel the number of dry months (moderate, severe, extreme or exceptional drought intensity class) during the autumn periods to generate the P1 parameter. The autumn periods present the onset of the agricultural seasons in Morocco and the annual productions depend on the amount of precipitation during these parts of the growing seasons. The second step is to calculate, for the same pixel, the number of dry months (only severe, extreme and exceptional drought classes) during the spring periods. The objective of this seasonal separation is to improve the classification accuracy between areas affected by the same drought intensity class. For example, two geographically separate areas belonging to the same drought frequency class according to the first parameter (P1) can be reclassified differently taking into account the presence or not of drought in spring periods (P2 parameter). In Morocco, the level of precipitation (in quantities and geographic repartition) in spring seasons is a critical condition to have a good crop yields mainly for rainfed cereals, which represent the most dominant agricultural areas. For this reason, there is a complementarity between the two parameters P1 and P2, but with no correlation. The high amount of precipitation only in autumn (or in spring) period separately does not necessarily lead to a high productivity at the end of the agricultural season in Morocco.

The procedure consists of preparing separate CDI databases, one for indices calculated from October to December each year since 2003, and the other for drought indices from January to April over the last twenty years. An in-house python model was developed to calculate the number of dry months per pixel and for each parameter (P1 vs P2). Then, this number is converted into drought frequencies ranging from zero (no dry months were recorded) to 100 (the pixel has experienced drought for the whole season and during the last 20 years).

The drought exposure index was then obtained by combining these two parameters P1 and P2 with the corresponding weighting factors. Since the impacts of drought during spring periods are higher than those happening in the beginning of the agricultural seasons in Morocco [37], the P2 parameter received a greater weight and was supposed two times more important than P1. Accordingly, the weights affected to P1 and P2 parameters are respectively 1/3 and 2/3 (Equation 1).

$$\text{Exposure} = 1/3 * P1 + 2/3 * P2 \quad (1)$$

Both parameters P1 and P2 were normalized and aligned the same way: a low (or high) score represented a low (vs high) value in terms of vulnerability [12]. The resulting exposure index values were merged into four drought frequency classes going from the less vulnerable areas (class 1) with a drought frequency less than 30% to the areas with high occurrence of drought (more than 50% for class 4). The resulting map (Figure 2) shows the occurrence of droughts according to the CDI generated from 2003 to 2022.

The map of exposure to drought (Figure 2) illustrates areas that have experienced a higher frequency of drought events over the past 20 years. The four frequency classes present in this map were evaluated by applying the normalization of categorical indicator values method [12]. The first category (class 1) corresponds to areas for which the frequency of drought is less than 30% (i.e., of the 140 months of CDI data studied, less than 42 months were dry). For classes 2 and 3, the observed drought frequencies are respectively between 30 and 40% (i.e., from 42 to 56 dry months for class 2) and between 40 and 50% (from 56 to 70 dry months out of 140 for class 3). Concerning areas with high level of exposure (class 4), the occurrence of drought exceeded 50%.

The map of exposure to drought shows that class 3 was the most dominant in terms of area (54.7% of the territory) and it concerned all agricultural zones and rangelands. This level of drought exposure (frequency between 40 and 50%) covered the provinces of the Oriental, the North, Saïss, Draa, Souss and the Southeast of the country. The second important class in terms of area was class 2, which occupied 29% of the national territory and corresponded to the non-irrigated agricultural areas and the rangelands of the south and the Oriental.

This map indicates also that the less exposed categories to drought (Class 1: irrigated perimeters and the mountains covered by forests) represented only 2.7% of the territory. However, the highly exposed areas to drought covered more than 13% of the national territory according to the CDI database analysis during the past twenty years and were located in the southern zones and in some provinces of the Oriental region.

3.2.2. Mapping the sensitivity to drought

Sensitivity to drought is approached through the principal characteristics of the system which interact with the exposure factors and that influence the extent of drought impacts. In this study, two main physical and natural factors were identified under sensitivity: soil types and land cover classes.

3.2.2.1. Soil and land cover classes vulnerability

Soil biophysical characteristics are an important factor to consider when studying drought vulnerability. Different types of soils retain different amounts of water and have different nutrient and mineral contents. Soil is an environment that generates and accumulates all the necessary nutrients for faunae and florae (nitrogen, phosphorus, calcium, potassium, iron, etc.), in addition to air and water. The absorption of these elements by vegetation through its root system is strongly dependent on water conditions. Moreover, the impact of a prolonged rainfall deficit varies according to the bio-physicochemical characteristics of the soil. Some naturally nutrient-rich soils with higher water holding capacities and appropriate structures and textures are more resistant to drought than other soils with low organic matter content and low water holding capacity.

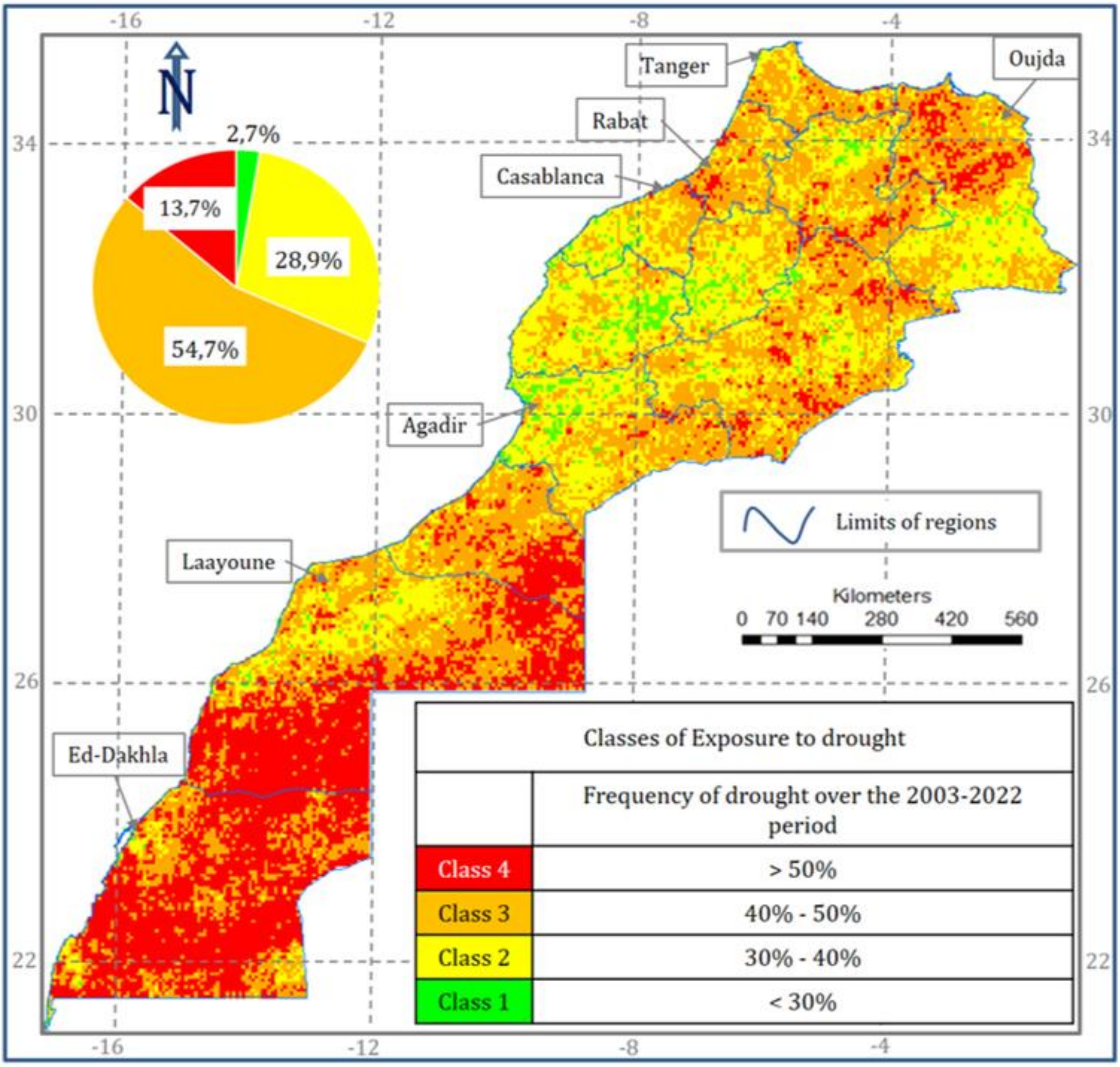

Figure 2. Map of the exposure to drought (2003-2022).

Mapping the soil types at national scale is very important to classify the different soil categories according to their degrees of vulnerability to drought. The map used in this study was a subset from the global map generated by the Soil Reference Information Center (ISRIC), which presents the texture classes of the surface layer (depth of 0.6m) at a spatial resolution of 250m [29]. For each of the main soil classes present in Morocco, the composition in clay, loam and sand was derived from the representation of textural classes according to the triangular diagram of textures of the American Department of Agriculture [39].

In the context of vulnerability to drought, there are strong links between soil characteristics and drought resilience. According to different studies [37,40], soils with dominant sandy composition (sands, loamy sands) present a high vulnerability to drought. These soils are characterized by a high porosity, have a low water retention capacity and are generally poor in organic matter and nutrients. These soil classes cover the south and some eastern zones in Morocco.

Heavier soils like loam and clay loams cover the majority of agricultural and forestry areas in Morocco. The vulnerability to drought of these soil categories is very low because the mixture of clay and loam guarantees a higher water retention capacity and allows aeration of the root zone, which increases crops resistance to rainfall deficit.

Soils having a sandy-clay and sandy-clay-loam texture with variable proportions are moderately vulnerable to drought. This soil class covers the central part of Morocco from the northeast (Oriental provinces) to the southwest (pre-Saharan region and the southern part of the Atlas Mountains).

On the other hand, concerning the land cover classes, the map generated at the national scale by classification includes nine land cover types, namely rainfed cultivated lands, irrigated areas, orchards, greenhouses, forests, rangelands, water bodies, artificial surfaces and bare soils. These land cover units were reclassified into homogeneous groups according to their degree of vulnerability to drought.

Figure 3 presents the synthetic map of the vulnerability to drought in relation to the soil factor (Figure 3a) and the map of land cover vulnerability (Figure 3b).

The map of soil vulnerability results from conversion of soil textures as presented in the initial map (SoilGrid) to their corresponding classes of vulnerability to drought. The resulting map (Figure 3a) shows an increasing degree of vulnerability from the north to the south and from the west to the eastern part of Morocco. Figures indicate that 38.7% of the national territory is composed of clay, clay-loam, loam and sandy clay soils, which present a high fertility and consequently a low vulnerability to drought. This soil vulnerability class is located in the northern and central parts of the country and corresponds to the agricultural and forest areas.

Soils presenting a moderate vulnerability to drought occupy 28.4% of the national territory and extend from the northeast to the southwest. Composed of a mixture of sand, clay and loam, these soils are covered by rangelands and desert vegetation, which tolerate soils with high proportion of sand. Finally, the southern part of Morocco is completely dominated by sand and loamy sand soils characterized by high vulnerability to drought. These poor soils occupy 32.9% of the national territory and are located in the desert area.

Figure 3b shows the relationship between land cover classes and their vulnerability to drought. In terms of rain dependency, the non-irrigated agricultural areas are highly vulnerable to drought because they typically rely on seasonal rainfall to provide the necessary water for crop production and livestock rearing. This category includes particularly cereal crops, given the importance and the dominance of the areas occupied by this crop in Morocco.

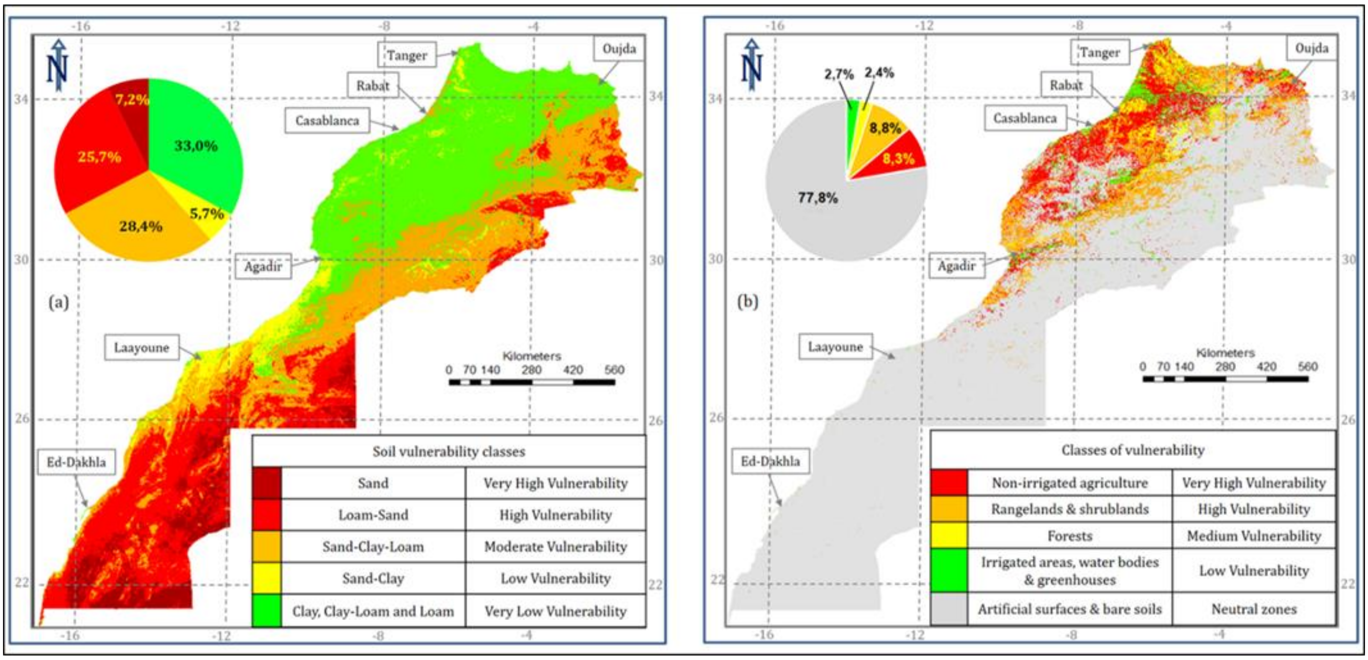

Figure 3. Map of the soil vulnerability (a) and the land cover vulnerability to drought (b).

Like rainfed cultivated areas, rangelands and natural vegetation fields are also sensitive to rainfall deficits and are highly vulnerable to drought. They have a lower degree of vulnerability than rainfed lands, since rangelands are reserved to grazing activities, whereas rainfed agricultural areas allow the generation of nutritional and commercial value-added products that have a direct impact on the population.

Forests are considered moderately vulnerable to drought in short-term because their sensitivity to seasonal precipitation deficit is negatively impacted after a long period due to the resilience of this ecosystem.

On the other hand, land cover classes presenting low vulnerability to drought are namely irrigated zones (including orchards and greenhouses using water from surface and/or groundwater resources) and water bodies (dams, lakes, reservoirs, rivers).

Finally, since the objective of this study is the mapping of agricultural vulnerability to drought, artificial surfaces (urban and rural buildings) and bare soils are not directly impacted by rainfall deficit due to the limited vegetative resources. For this reason, these land cover types were classified as neutral zones.

3.2.2.2. Sensitivity index

As for the drought exposure index, the sensitivity index results from the weighted combination between soil and land cover vulnerability classes, which are the main factors identified under sensitivity. While soil type tends to be a static parameter and is inherent in the system, land cover might be altered by human activities. Some examples of changes are decreasing of natural vegetation ecosystems (forests, rangelands and some agricultural areas) due to the impact of artificial surfaces development (urban and industrial constructions, mining zones, transportation facilities, etc.), and sometimes due to natural hazards (forest fires, floods, etc.). For this reason, the land cover factor was given a higher weight than soil class's parameter.

Therefore, the weights assigned to soil types and land cover parameters are respectively 1/3 and 2/3. Equation 2 shows how these two factors were aggregated.

$$\text{Sensitivity} = 1/3 * \text{Soil vulnerability} + 2/3 * \text{Land cover vulnerability} \quad (2)$$

According to the Vulnerability Sourcebook [12], both parameters soils and land cover were normalized and aligned the same way (a high score represented a high value in terms of vulnerability). The resulting sensitivity index values were merged into four sensitivity classes going from the less sensitive areas (irrigated agriculture on clay-loam soils) to the areas with high sensitivity to drought (rainfed cereals on sandy soils). Figure 4 presents the resulting map of sensitivity to drought.

The map (Figure 4) shows that areas with low sensitivity to drought are located mainly in the Tangier-Tetouan-Al-Hoceima and Rabat-Sale-Kenitra regions and partially of the Fez-Meknes and Beni-Mellal-Khenifra regions. This category occupied 5% of the national territory and concerned the irrigated zones on favorable soil type and the mountains (Rif and Atlas). Additionally, areas moderately sensitive to drought occupied about 16% of the Moroccan territory and corresponded to the majority of regions covered mainly by rainfed seasonal crops on clay-loam soils. These two first classes merged represent 21% of the national territory and are located in the most fertile agricultural zones.

The map in Figure 4 shows also that 19% of the territory was highly sensitive to drought. This concerns rainfed agricultural areas and rangelands located on sandy clay-loam soils in the eastern, central and southern parts of Morocco.

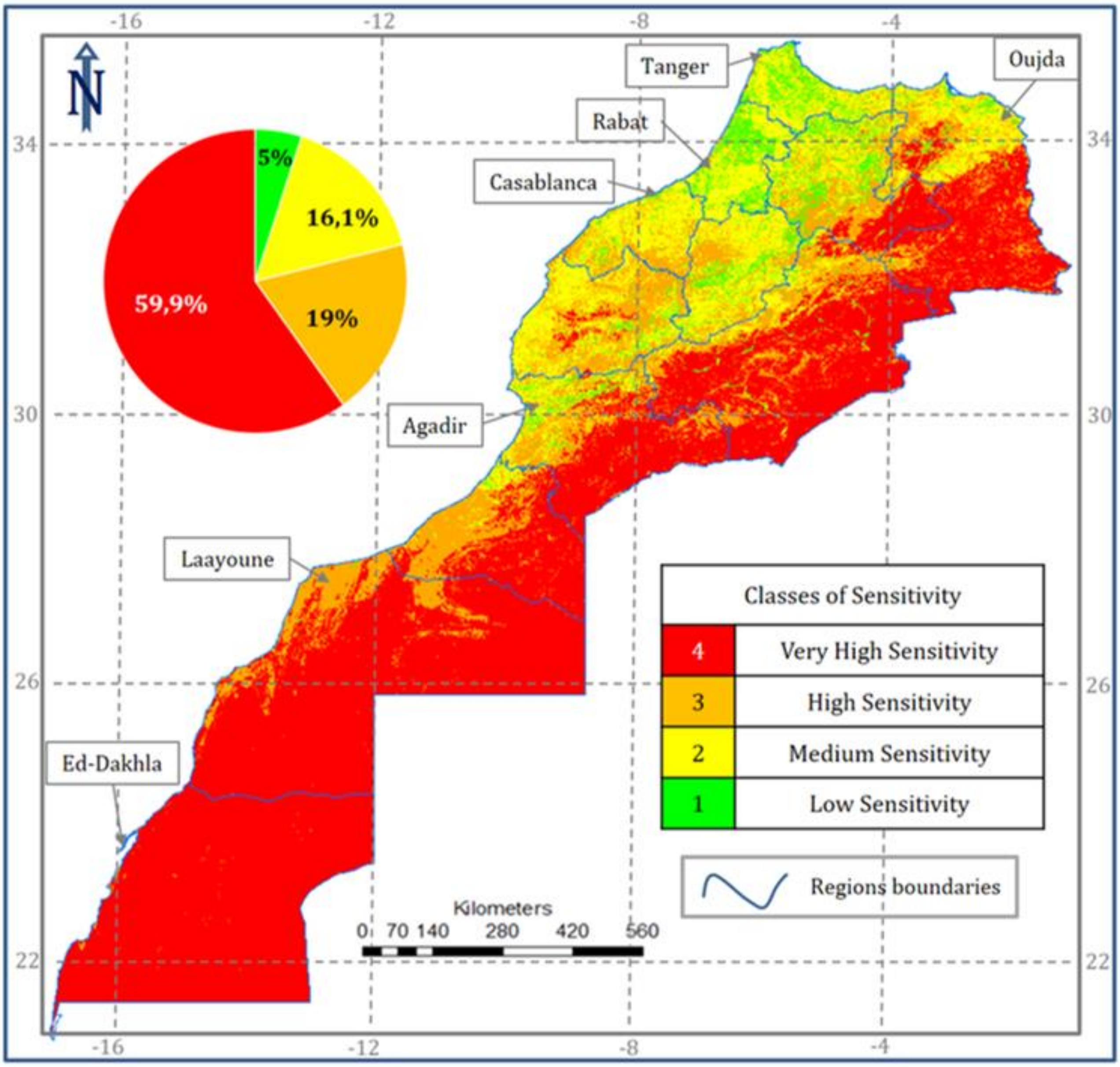

Figure 4. Map of the sensitivity to drought.

Finally, areas presenting a very high sensitivity to drought, stretching from the northeast to the south of Morocco, covered about 60% of the national territory. This category included all the desert regions and some provinces of the Souss-Massa, Draa-Tafilalet and Oriental regions. The regions of Fez-Meknes (eastern part) and Marrakech-Safi (Chichaoua province) were also partially concerned by this class of high sensitivity to drought. The geographical distribution of this class reflects the combination of the biophysical nature of these bare sandy-loam soils and the scarcity of rainfall.

3.2.3. Potential impact

In accordance with the Vulnerability Sourcebook [12], exposure (Figure 2) and sensitivity (Figure 4) in combination determine the potential impact of climate change. For example, in the context of drought vulnerability, long period rainfall deficit (exposure) in combination with non-irrigated crops and sandy soils (sensitivity) will result in loss of yields and income (potential impact). Concerning the weighting approach, we considered each of the two vulnerability components (exposure and sensitivity) as important as the other. For this reason, the two factors were equally weighted (Equation 3).

$$\text{Potential Impact} = 1/2 * \text{Exposure} + 1/2 * \text{Sensitivity} \quad (3)$$

The resulting map of the potential impact of drought in Morocco (Figure 5) illustrates the distribution of four main categories going from areas where the impact of climate change was low to the areas where the potential impact was high.

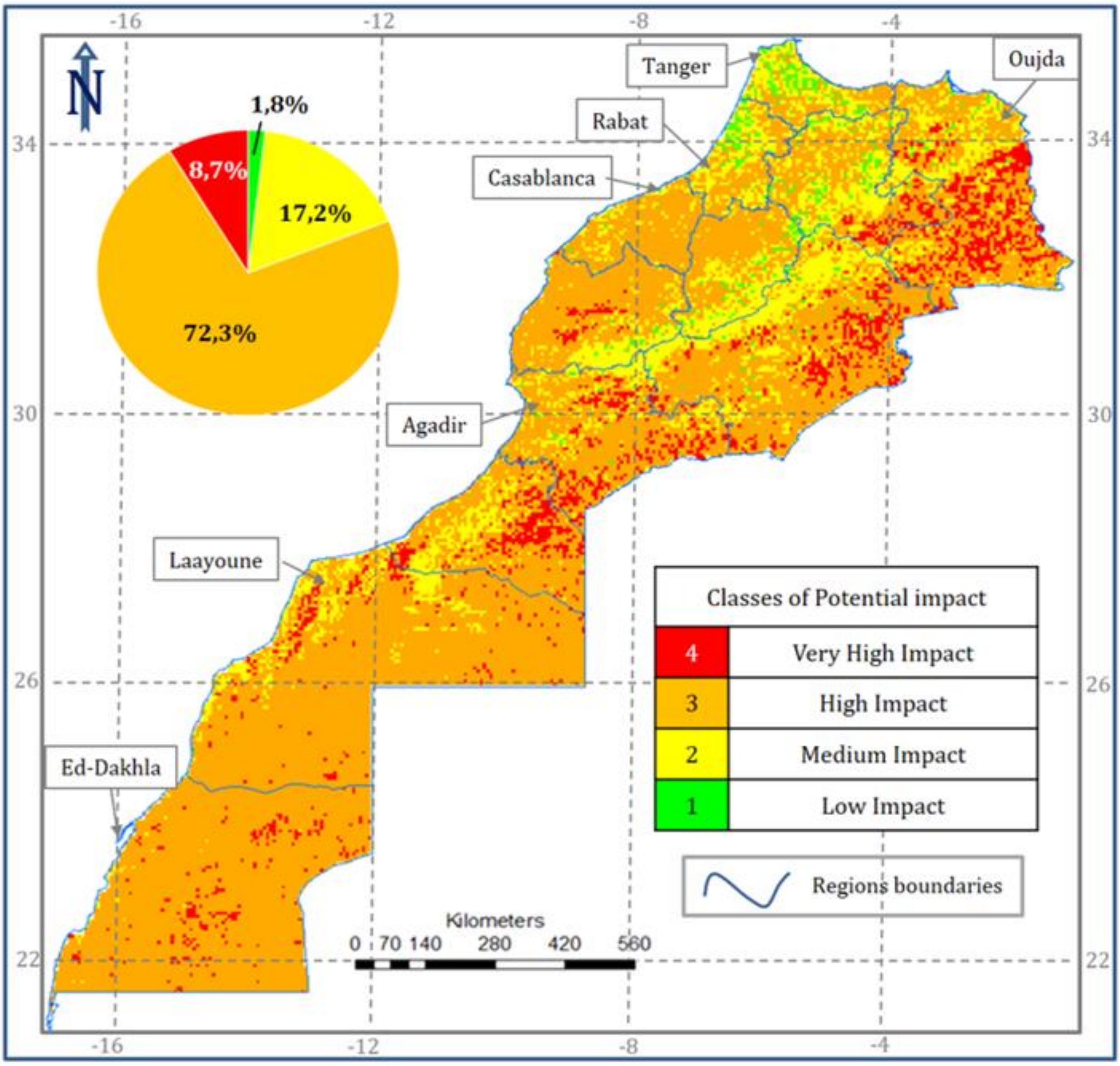

Figure 5. Map of the potential impact.

The map of potential impact shows that less than 2% of the national territory presented low impact of drought on the natural resources. This category is located mainly in the north of the country and corresponds to forest and permanent irrigated areas. The second category (medium potential impact of drought) is located also in the forest (Rif and Atlas Mountains) and in some irrigated areas. These two classes of potential impact to drought covered 19% of the national territory, and they presented a high resilience to short-term drought due to their biophysical characteristics (rainfall, temperatures, vegetation cover, soil types, topography, etc.).

Areas with high potential impact of drought were dominant (72.3% of the territory) and corresponded to both agricultural zones, rangelands as well as the desert areas in the south of Morocco. For these areas, the impact of drought episodes frequencies combined with inadequate soil texture resulted in a loss of agricultural yields and consequently loss of income.

The last category concerns the rangelands in the Oriental region, Draa and some southern and southeastern provinces where the potential impact of drought was very high. For these zones, vegetation development is strongly dependent on precipitation.

3.2.4 Adaptive capacity

In Morocco, the department in charge of population planning (HCP) has traditionally measured the poverty rate using the monetary approach, which assesses a household's income and expenditure. This monetary approach, initially developed by the World Bank, has reached its limits because poverty is more than just a lack of money. Recent efforts have shifted towards adopting a multidimensional approach that takes into account other indicators such as education, health, housing, and access to basic services [41].

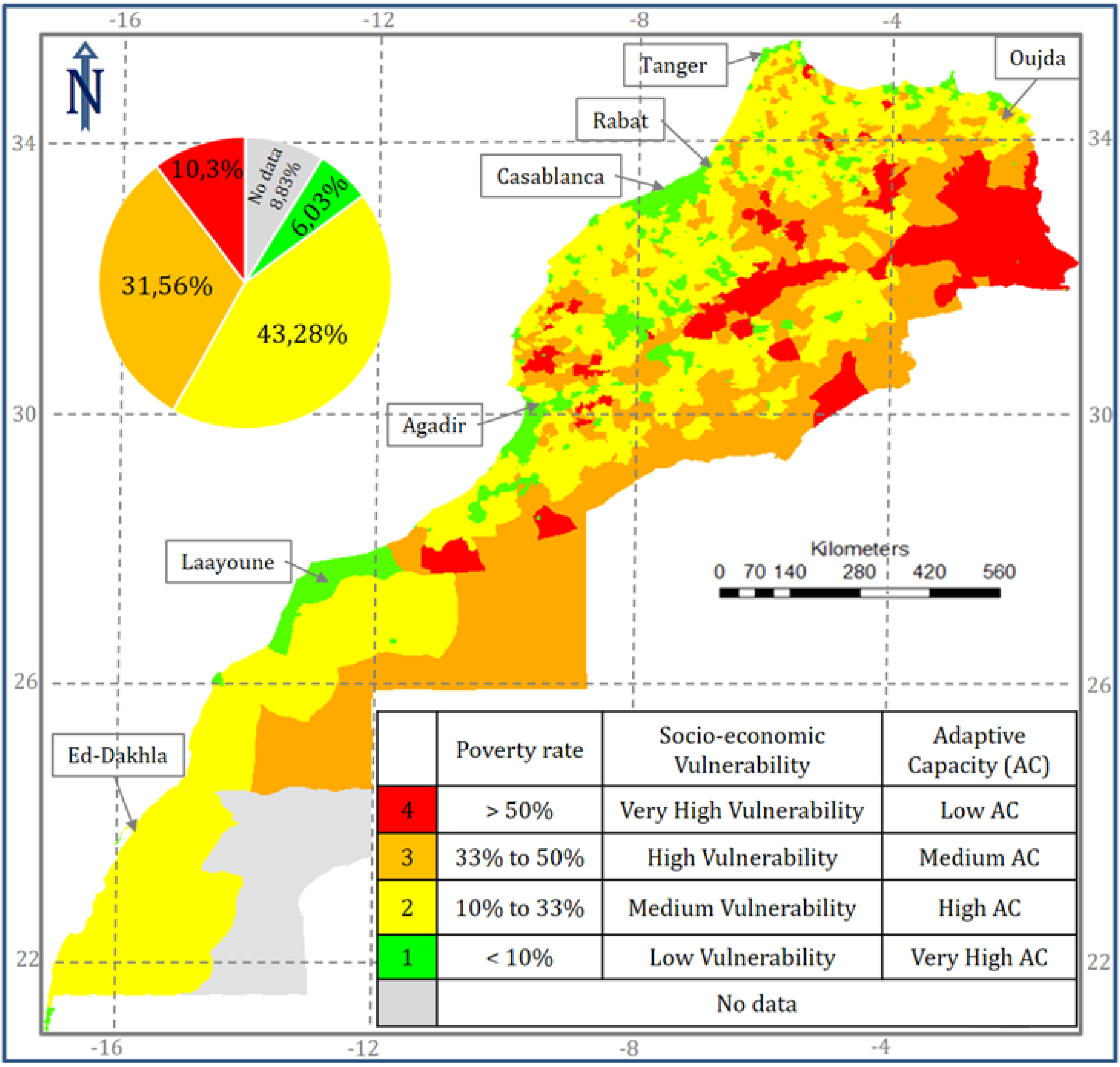

Figure 6. Map of the adaptive capacity to drought.

The methodology adopted by the HCP to calculate and monitor the poverty rate is based on a global approach including both monetary and a multidimensional approach. Since poverty affects people's daily lives and well-being in many ways, this global approach consists of identifying deprivations based on unsatisfied needs in education, health and living conditions (food security, access to clean water and electricity, housing conditions) from the analysis of the 2014 general population census results. The adopted approach recognizes that poverty affects individuals differently depending on their gender, age group or living in urban vs rural area. A score aggregating the different deprivations is then established by assigning weights to each of the three main categories

(1/3 for education, 1/3 for health and 1/3 for living conditions). This scoring system allows for better understanding of the multifaceted nature of poverty and its underlying causes.

In the present study, we used a global poverty index that was defined by the HCP based on a typology of the general population census results corresponding to the 2004-2014 period. In Morocco, these results are available at the regional, provincial and communal levels in tabular format. The data corresponding to the poverty index at communal scale was retrieved, spatialized and reclassified into levels of socio-economic vulnerability. According to the HCP, a population group is considered multi-dimensionally poor if his deprivation score is above the poverty line, set by convention at 33% [35].

Figure 6 illustrates the distribution of the different socio-economic vulnerability classes at the communal level. To these gridded poverty classes were defined targeted groups of population with different adaptive capacity to drought conditions.

Figure 6 shows that the municipalities and the communes located next to the big cities presented a very low poverty rate and consequently they had a very high adaptive capacity. These 407 communes covered only 6% of the national territory.

The HCP figures indicated also that more than 43% of the national territory (739 communes) was vulnerable to poverty but under the conventional poverty line. This concerned all the areas where agriculture, industry, tourism and artisanal activities contributed in different proportions to the population income. These rural communes with medium vulnerability presented a high capacity of adaptation to reduce drought impacts.

Concerning the communities above the national poverty line, 260 rural communes were considered highly vulnerable to drought and presented a medium adaptive capacity to address climate change impacts. This class of socio-economic vulnerability corresponded to a poverty rate between 33 and 50% and covered about 32% of the national territory.

Finally, the communes with a very high level of vulnerability covered about 10% of the national territory (93 communes) and were located in the provinces of Oriental, Atlas Mountains and other zones in the south. These very high vulnerable communes had a low adaptive capacity to alleviate drought impacts. For example, the rural commune "Oulad Mhammed" in Taourirt province had a poverty rate in 2014 of 90.1% and the rural commune "Tabaroucht" in Azilal province had a poverty rate of 85.6%. This explains the absence of the majority of the living conditions for the population in these two communes. In case of prolonged periods of drought in these vulnerable communities, the impacts would be heavily devastating on natural resources (crop yields and livestock losses, limited access to drinking water, land degradation and consequently desertification).

The contribution of the global poverty index in the study of structural vulnerability to drought is very important in two different ways. On one hand, it allows identifying communities with high adaptive capacity to climate hazards in order to mitigate the potential impacts, and on the other hand, this parameter highlights areas where drought can have adverse impacts on the poorest populations. In other words, groups in low and medium vulnerability classes (and who have permanent and non-agricultural incomes) are generally more resilient to climate changes. This adaptive capacity reduces the potential impact of climate effects and therefore mitigates vulnerability to drought. On the other hand, poor and highly vulnerable populations are the first to suffer the impacts of drought and constitute a pressure factor that threatens natural resources.

The combination between the potential impact and adaptive capacity maps to generate the synthetic structural drought vulnerability map is presented in the following.

4. Results and discussion

This section of the study consists in generating a composite drought vulnerability index by aggregating the potential impact and adaptive capacity. The gridded representation of this index involves analyzing and mapping the susceptibility of different communities to the impacts of a drought event. This process takes into account all the factors described above namely; climate conditions, soil characteristics, land cover classes and global poverty index.

The methodology adopted to generate this structural vulnerability index was based on an aggregation of the composite indicator of potential impact with adaptive capacity using a visual overlay analysis.

All the indicators used in this study to calculate the potential impact were aligned in the same way. Concerning the adaptive capacity aggregation with the potential impact, it is important to take into account the offsetting between these two components. Indeed, adaptive capacity has a positive influence on vulnerability to drought. It reflects the ability of population to adapt to and recover from drought when it occurs.

According to the vulnerability sourcebook [12], high values for adaptive capacity (rich communities) can offset high drought impact values, and this leads to low vulnerability values in spite of high potential impact. In the same way, areas with high potential impact and low adaptive capacity can be considered as vulnerable areas to drought (hotspots).

Unlike the methodology adopted for the other components of the vulnerability (Exposure, Sensitivity and potential impact) which is based on the weighted arithmetic aggregation, the visual overlay analysis consists in applying GIS functionalities (Map Algebra, Raster calculator) to generate a map where areas corresponding to different combinations between the potential impact and the adaptive capacity components can be highlighted graphically.

The Moroccan adaptive capacity layer includes more than 1500 polygons representing the rural communes and municipalities with values corresponding to the four socio-economic vulnerability classes. Both adaptive capacity and potential impact layers are first standardized per unit area (pixel size) and then combined to generate the resulting vulnerability map.

For each of the potential impact (P.I.) levels, Table 2 shows the proportion of the national territory corresponding to each of the adaptive capacity (A.C.) classes.

By identifying areas more susceptible to drought, planners can prepare mitigation strategies, targeted responses and resources distribution plans that address the specific needs of the risk. The mapping process could also indicate where additional data collection efforts may be necessary in order to provide assistance before, during or after an actual occurrence.

Table 2. Proportions of the territory for each potential impact and adaptive capacity combination.

Potential Impact (P.I.)	Adaptive Capacity (A.C.)				
	Very high A.C. (%)	High A.C. (%)	Medium A.C. (%)	Low A.C. (%)	A.C. (no data) (%)
Low P.I.	0.15	1.01	0.43	0.24	0
Medium P.I.	1.99	7.41	4.80	2.96	0
High P.I.	3.63	32.59	22.84	5.23	8.01
Very high P.I.	0.27	2.46	3.49	2.10	0.38

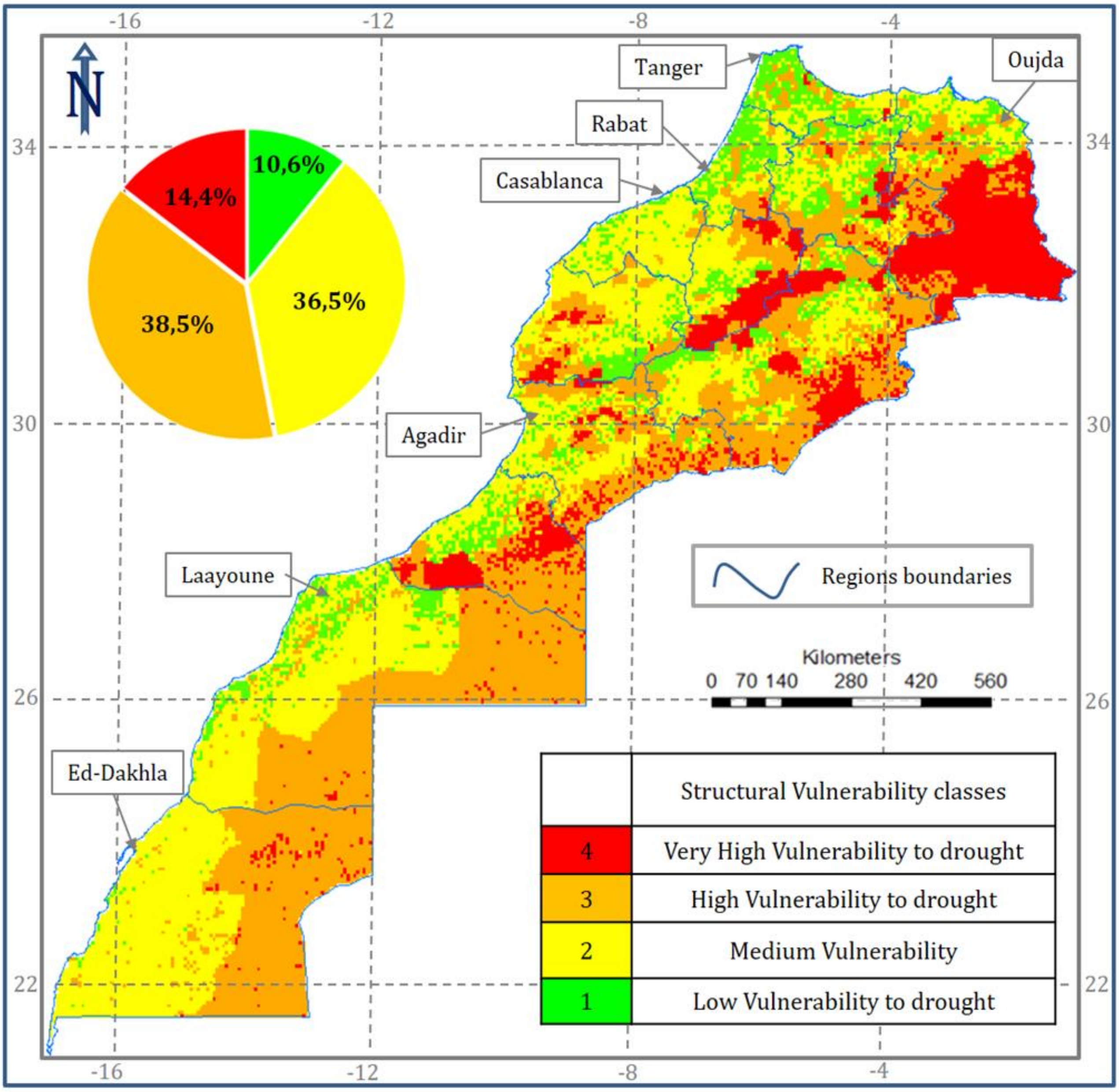

Figure 7. Map of the structural vulnerability to drought in Morocco. Four levels of vulnerability: (1) green: low score, (2) yellow: medium, (3) orange: high and (4) red: very high level of vulnerability to drought.

The different combinations shown in Table 2 were grouped into four main levels of vulnerability to drought. Low vulnerability values correspond to the combination of low to medium potential impact and high to very high adaptive capacity and vice versa, high vulnerability values result from the union of high to very high impact and low adaptive capacity. Table 2 shows also the intermediate vulnerability levels resulting from the mixture between different intermediate potential impact and adaptive capacity classes. The graphic representation of these merged classes of the structural vulnerability to drought in Morocco is illustrated in Figure 7.

The geographic distribution of the four vulnerability classes at national scale (Figure 7) shows a slight dominance of areas with high to very high vulnerability to drought. Indeed, these two classes (3 and 4) cover about 53% of the national territory (331.425 km^2) and extend from the northeast to the south. With this proportion, it means that a substantial portion of agricultural land is at a risk.

The Oriental provinces and some areas in the Atlas and in the south of the country are very highly vulnerable to drought, representing around 14% of the national territory. In these areas, land cover is dominated by bare soils and rangelands on unfavorable soils (loam-sands and sand-clay-loams), which are reliant upon rainfall. Moreover, these zones are characterized by a very low adaptive capacity, which increase considerably the vulnerability to drought and to climate change in general.

Areas with high vulnerability to drought (class 3) represent about 39% of the national territory and concern almost the totality of the provinces located in the east and southeastern boundary. These regions are characterized by low amount of precipitation and high temperatures coupled with pressures of population growth and poverty. The spatial variation of this level of vulnerability affects desert areas as well as rain-fed agricultural zones.

On the other hand, areas with low to medium vulnerability to drought (classes 1 and 2) represent about 47% of the Moroccan territory (294.700 km^2). This concerns the main irrigated areas (Gharb, Loukkos and northwest, Tadla, Doukkala, Al Haouz, Souss-Massa, Ouarzazate, Tafilalet and Moulouya) as well as forests (Rif and Atlas), oasis zones (Draa, Tafilalet) and some coastal zones.

Areas with low vulnerability to drought (class 1) represent only 10.6% of the national territory (66,175 km^2) and correspond essentially to irrigated zones where irrigation had become increasingly popular as a means of combating dry spells and helping farmers control water distribution precisely. Similarly, forest areas are more resistant to drought and can be impacted only after a long period of rainfall deficit.

However, although the favorable components of the vulnerability chain for these zones (high adaptive capacity offsetting the impact of drought), agriculture and livestock remain vulnerable to droughts. In addition, some forests of the Rif and the Atlas Mountains are in a very worrying state of degradation (forest fires, health attacks, overexploitation of wood, etc.), which increases the level of vulnerability of these ecosystems to drought and climate hazards in general.

Locally, the Oriental region is the most affected by the highest drought vulnerability level. Indeed, about 60% of the region is categorized very highly vulnerable to drought and a little more than 20% of the region is highly vulnerable. This part of the region is dominated by rangelands, rainfed agriculture and bare soils. Only 20% of the region is located in low to medium vulnerable areas to drought and this concern the coastal areas, the Moulouya irrigation perimeter and nearby the principal cities (Oujda, Saidia and Nador).

Similarly, the Draa-Tafilalet region is also dominated by areas of high and very high vulnerability to drought, occupying respectively 45.8% and 19% of the regional territory. The western part of the region presents a low to medium vulnerability to drought, and it is mainly covered by oases of Draa-Tafilalet and by the Ouarzazate and Tafilalet irrigated perimeters.

Concerning Beni Mellal-Khenifra, about 59% of the region presents a high to very high vulnerability to drought nearby Khouribga, Khenifra and Azilal provinces. The low (10.2%) to medium (31.2%) vulnerability classes cover the Tadla irrigated perimeter (Beni Mellal and Fquih Ben Saleh provinces).

The eastern part of Fez-Meknes region is dominated by areas categorized high to very high vulnerable to drought, presenting about 48% of its territory (Boulemane province) in the proximity of the Oriental rangelands. The provinces of Fez, Meknes, Ifrane, Sefrou and partly the province of Taounate present a low to medium vulnerability to drought.

Table 3. Proportions of drought vulnerability areas per region.

Regions of Morocco	Levels of vulnerability to drought			
	Low (%)	Medium (%)	High (%)	Very high (%)
Tanger-Tetouan-AlHoceima	47.88	35.02	15.47	1.63
Oriental	7.45	13.16	20.29	59.10
Fes-Meknes	22.48	29.33	37.50	10.68
Rabat-Sale-Kenitra	40.52	39.30	18.65	1.53
Benimellal-Khenifra	10.24	31.20	25.28	33.27
Casablanca-Settat	14.17	81.55	4.28	0
Marrakech-Safi	13.92	54.66	23.11	8.30
Draa-Tafilalet	10.11	25.02	45.83	19.03
Souss-Massa	8.60	34.99	44.49	11.91
Guelmim-Oued-Noun	11.11	21.42	41.11	26.36
LaayouneBoujdour-Sakia-Al-Hamra	8.49	40.20	49.89	1.42
Eddakhla-Oued-Eddahab	0.62	49.94	47.30	2.13

The three regions in the northwest (Tangier-Tetouan-Al-Hoceima, Rabat-Sale-Kenitra and Casablanca -Settat) are characterized by favorable weather conditions, advantageous soil textures, adequate land covers and a high adaptive capacity. Therefore, these regions present a high proportion of areas with low to medium vulnerability to drought. The twelve Moroccan regions are listed in Table 3, with the values of relative proportions of each vulnerability to drought level.

The high sensitivity to drought poses significant challenges for the affected regions and the country as a whole. The prolonged areas of drought indicate a widespread and persistent problem that demands immediate attention. One of the consequences of such extensive drought-prone areas is the impact on agriculture, as crop yields are likely to be severely affected. Moreover, water scarcity has become a pressing issue in these drought-prone areas. As rainfall tends to be increasingly insufficient, water sources such as rivers, lakes, and reservoirs dry up or become critically low. This affects not only agricultural irrigation but also it has severe implications for drinking water supply and other industrial needs.

5. Conclusion

Droughts can have severe impacts on natural resources, communities and ecosystems, especially in regions already vulnerable due to poverty and/or limited resources. Vulnerability to drought can vary greatly depending on the adaptive capacity of a community or ecosystem. In areas where adaptive capacity is low, droughts may lead to food shortages, increased poverty rates or even forced migration.

In Morocco, drought has a significant impact on the agricultural productivity because approximately 85% of agricultural areas rely on rainfall, making it highly susceptible to the effects of climate-related risks. Due to its frequent occurrence and long-lasting impact, drought is regarded as a structural component of Morocco's climate.

By evaluating the available data, it is evident that Morocco is globally vulnerable to drought due to various factors such as rainfall deficit, population growth, and overuse of water resources. The country's economy is heavily dependent on agriculture, which in turn depends on rainfall, making it highly susceptible to prolonged dry spells specifically during critical agricultural periods.

This study allowed generating a comprehensive map that highlights which areas of the country are most susceptible to drought and other weather-related disasters. The map of vulnerability to drought is the result from the combination of several biophysical variables including meteorological factors (precipitation, SPI, temperatures and evapotranspiration), remote sensing indices (vegetation index, land surface temperature and multi-temporal high-resolution satellite data to generate land cover maps), soil factor and the population status in terms of the poverty distribution all over the country.

The exposure index, which is one of the main components of the structural vulnerability to drought, allowed us to draw first conclusions about the most vulnerable areas. This index has the advantage that it is applicable for prospective assessments of drought occurrences based mainly on remote sensing data.

By highlighting vulnerable regions, the maps are playing an important role in helping planners and decision-makers take proactive measures to mitigate the effects of future droughts, develop effective drought response plans and allocate resources where they are most needed. Therefore, the map of structural vulnerability to drought in Morocco constitutes a decision support tool for resource management in case of drought.

Concerning the methodological approach, it is important to highlight the role of spatial observation, which enabled producing indicators that are not only simple to compute but also relevant, accurate and easily accessible. The generated maps provide a comprehensive understanding of drought conditions by considering multiple meteorological variables combined to other biophysical parameters. This composite approach allows capturing the complex interactions between these factors and their impact on agricultural productivity. Moreover, these global indicators involved in the study of vulnerability can be adapted and applied to other similar contexts, making this methodology highly transferable and valuable.

Other indicators can be added to enhance the study of the structural vulnerability to drought. These may include measurements that demonstrate changes in ground and surface water resources, the distribution of livestock, and the identification of drought-resistant crops, etc. By integrating all of these biophysical parameters, a more comprehensive and detailed mapping of structural vulnerability to drought can be achieved. This could serve as a valuable subject for future research.

Acknowledgement

The present study was carried out by the use of various data that made available periodically. The MODIS/LST products were retrieved from the online Data Pool, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science Center (EROS), https://lpdaac.usgs.gov/data_access/data_pool. Precipitation estimates (CHIRPS products), anomalies of vegetation indices (NDVIa) and evapotranspiration generated from SSEBop model were monthly downloaded from the USGS FEWS NET Data Portal. Other valuable products (Soil maps, Sentinel_2 images, population poverty in Morocco) were retrieved from different platforms. We would like to extend our sincere gratitude to all the data providers for their cooperation and willingness to process and make all the data open access. Without the availability of this valuable data, this study would not have been feasible with accuracy and reliability of our results.

Author contributions

Noureddine Bijaber: Satellite data collection, Preparation and processing, Methodology and Writing-Original draft preparation. **Atmane Rochdi:** Results validation and Writing-reviewing. **Mohammed Yessef:** Results validation and Writing-reviewing. **Houda El Yacoubi:** Results validation and Writing-reviewing.

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Khorrami, B., & Gündüz, O. (2022). Detection and analysis of drought over Turkey with remote sensing and model-based drought indices. Geocarto International, 37(26), 12171-12193. https://doi.org/10.1080/10106049.2022.2066197
2. Observatoire du Sahara et du Sahel. (2013). Vers un système d'alerte précoce à la sécheresse au Maghreb. OSS. Collection Synthèse, 4. OSS: Tunis.
3. World Bank. (2022). Country Climate and Development Report: Morocco. Washington, DC: World Bank
4. Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M., & Kahlenborn, W. (2014). The Vulnerability Sourcebook: Concept and guidelines for standardised vulnerability assessments.
5. Hoque, M., Pradhan, B., Ahmed, N., & Alamri, A. (2021). Drought vulnerability assessment using geospatial techniques in southern Queensland, Australia. Sensors, 21(20), 6896. https://doi.org/10.3390/s21206896
6. West, H., Quinn, N., & Horswell, M. (2019). Remote sensing for drought monitoring & impact assessment: Progress, past challenges and future opportunities. Remote Sensing of Environment, 232, 111291. https://doi.org/10.1016/j.rse.2019.111291
7. Wilhite, D. A. (2000). Drought as a natural hazard: Concepts and Definitions. Drought: A Global Assessment.
8. Svoboda, M., & Fuchs, B. (2016). Handbook of Drought Indicators and Indices. Integrated Drought Management Programme (IDMP)
9. Iglesias, A., Cancelliere, S., Gabiña, D., López-Francos, A., Moneo, A., & Rossi, G. (2007). Medroplan Drought Management Guidelines and Examples of Application; European Commission. MEDA-Water Programme: Zaragoza, Spain.
10. RICCAR (2017). Training manual on the integrated vulnerability assessment methodology.
11. Szaboova, L. (2023). Climate change, migration and rural adaptation in the Near East and North Africa region. Food and Agriculture Organization of the United Nations.
12. Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M. & Kahlenborn, W. (2017). The vulnerability sourcebook. Concept and guidelines for standardized vulnerability assessments. Risk Supplement: How to apply the approach with the IPCC AR5 risk concept.
13. Bijaber, N., El Hadani, D., Saidi, M., Svoboda, M. D., Wardlow, B. D., Hain, C. R., ... & Rochdi, A. (2018). Developing a remotely sensed drought monitoring indicator for Morocco. Geosciences, 8(2), 55. https://doi.org/10.3390/geosciences8020055
14. Fragaszy, S. R., Jedd, T., Wall, N., Knutson, C., Fraj, M. B., Bergaoui, K., ... & McDonnell, R. (2020). Drought monitoring in the Middle East and North Africa (MENA) region: participatory engagement to inform early warning systems. Bulletin of the American Meteorological Society, 101(7), E1148-E1173. https://doi.org/10.1175/BAMS-D-18-0084.1
15. Svoboda, M. D., Fuchs, B. A., Poulsen, C. C., & Nothwehr, J. R. (2015). The drought risk atlas: enhancing decision support for drought risk management in the United States. Journal of Hydrology, 526, 274-286. https://doi.org/10.1016/j.jhydrol.2015.01.006
16. Funk, C. C., Peterson, P. J., Landsfeld, M. F., Pedreros, D. H., Verdin, J. P., Rowland, J. D., ... & Verdin, A. P. (2014). A quasi-global precipitation time series for drought monitoring. US Geological Survey, 832. https://dx.doi.org/10.3133/ds832
17. McKee, T. B., Doesken, N. J., & Kleist, J. (1995). Drought monitoring with multiple time scales. Proceedings of the Conference on Applied Climatology.
18. McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology.
19. Senay, G. B., Velpuri, N. M., Bohms, S., Budde, M., Young, C., Rowland, J., & Verdin, J. P. (2015). Drought monitoring and assessment: remote sensing and modeling approaches for the famine early warning systems network. Hydro-meteorological Hazards, Risks and Disasters, 233-262. https://doi.org/10.1016/B978-0-12-394846-5.00009-6
20. Hain, C. R., Crow, W. T., Mecikalski, J. R., Anderson, M. C., & Holmes, T. (2011). An intercomparison of available soil moisture estimates from thermal infrared and passive microwave remote sensing and land surface modeling. Journal of Geophysical Research: Atmospheres, 116, D15107. https://doi.org/10.1029/2011JD015633
21. Wan, Z. (2006). MODIS land surface temperature products users' guide. Institute for Computational Earth System Science, University of California: Santa Barbara, CA, USA, 805, 26.
22. Wan, Z., Zhang, Y., Zhang, Q., & Li, Z. L. (2002). Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data. Remote Sensing of Environment, 83(1-2), 163-180. https://doi.org/10.1016/S0034-4257(02)00093-7
23. Senay, G. B., Bohms, S., Singh, R. K., Gowda, P. H., Velpuri, N. M., Alemu, H., & Verdin, J. P. (2013). Operational evapotranspiration mapping using remote sensing and weather datasets: A new parameterization for the SSEB approach. JAWRA Journal of the American Water Resources Association, 49(3), 577-591. https://doi.org/10.1111/jawr.12057
24. Bijaber N., El Hadani, D., Saidi, M., Svoboda, M. D., Poulsen, C. C., Hain, C. R., Wardlow, B. D., & Yessef, M. (2017). Suivi mensuel de la sécheresse au Maroc par techniques basées sur l'indice composite. GéoObservateur n°23, Rabat, Marocco, 25-37

25. Jia, H., Chen, F., Zhang, J., & Du, E. (2020). Vulnerability analysis to drought based on remote sensing indexes. International Journal of Environmental Research and Public Health, 17(20), 7660. https://doi.org/10.3390/ijerph17207660
26. Tran, H. T., Campbell, J. B., Tran, T. D., & Tran, H. T. (2017). Monitoring drought vulnerability using multispectral indices observed from sequential remote sensing (Case Study: Tuy Phong, Binh Thuan, Vietnam). GIScience & Remote Sensing, 54(2), 167-184. https://doi.org/10.1080/15481603.2017.1287838
27. Hanadé Houmma, I., Gadal, S., El Mansouri, L., Garba, M., Gbetkom, P. G., Mamane Barkawi, M. B., & Hadria, R. (2023). A new multivariate agricultural drought composite index based on random forest algorithm and remote sensing data developed for Sahelian agrosystems. Geomatics, Natural Hazards and Risk, 14(1), 2223384. https://doi.org/10.1080/19475705.2023.2223384
28. Badraoui, M. (2006). Connaissance et utilisation des ressources en sol au Maroc. Rapport thématique, 50.
29. Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., ... & Kempen, B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. PLoS One, 12(2), e0169748. https://doi.org/10.1371/journal.pone.0169748
30. Reichhuber, A., Gerber, N., Mirzabaev, A., Svoboda, M., López Santos, A., Graw, V., ... & Jia, X. (2019). The land-drought nexus enhancing the role of land-based interventions in drought mitigation and risk management. In United Nations Convention to Combat Desertification, Bonn.
31. Inglada, J., Vincent, A., Arias, M., Tardy, B., Morin, D., & Rodes, I. (2017). Operational high resolution land cover map production at the country scale using satellite image time series. Remote Sensing, 9(1), 95. https://doi.org/10.3390/rs9010095
32. Van Thinh, T., Duong, P. C., Nasahara, K. N., & Tadono, T. (2019). How does land use/land cover map's accuracy depend on number of classification classes?. Sola, 15, 28-31. https://doi.org/10.2151/sola.2019-006
33. Winsemius, H. C., Jongman, B., Veldkamp, T. I., Hallegatte, S., Bangalore, M., & Ward, P. J. (2018). Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. Environment and Development Economics, 23(3), 328-348. https://doi.org/10.1017/S1355770X17000444
34. UNDRR (2021). Global Assessment Report on Disaster Risk Reduction GAR, Special Report on Drought.
35. Haut-Commissariat au Plan. (2017). Principaux résultats de la cartographie de la pauvreté multidimensionnelle 2014. Paysage territorial et dynamique, Rapport.
36. Murthy, C. S., Laxman, B., & Sai, M. S. (2015). Geospatial analysis of agricultural drought vulnerability using a composite index based on exposure, sensitivity and adaptive capacity. International Journal of Disaster Risk Reduction, 12, 163-171. https://doi.org/10.1016/j.ijdrr.2015.01.004
37. Balaghi, R., Jlibene, M., Tychon, B., & Eerens, H. (2012). La prédiction agrométéorologique des rendements céréaliers au Maroc. Institut National de La Recherche Agronomique, Maroc.
38. Bijaber, N., & Rochdi, A. (2019, November). Development of a comprehensive remote sensing technique for drought monitoring in Morocco. In Conference of the Arabian Journal of Geosciences, 311-313. https://doi.org/10.1007/978-3-030-72896-0_70
39. de Forges, A. R., Feller, C., Jamagne, M., & Arrouays, D. (2008). Perdus dans le triangle des textures. Etudes et gestion des Sols, 15(2), 97-111.
40. Motib, I., Batchi, M., & Fatah, F. (2020). Conservation Des Ressources Naturelles Pour Une Sécurité Alimentaire Durable Au Maroc. European Scientific Journal, 16, 240-260.
41. Alkire, S., Conconi, A., & Seth, S. (2014). Multidimensional Poverty Index 2014: Brief methodological note and results. OPHI briefing, 19.