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Determination of the Status of Desertification in the Capital of Mauritania and Development of A Strategy for Combating It

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Abstract: Mauritania, located in the Western Sahara, is one of the least developed countries in the Sahara Desert. Its capital, Nouakchott, which is home to 23% of its population, suffers from soil erosion from the Sahara and saltwater intrusion from the Atlantic Ocean. The local environment is under pressure from the combined effects of climate and socio-economic factors, with desertification being recognized as the greatest threat to life. In this context, high-resolution remote sensing images of Nouakchott obtained during the winters of 1985, 1988, 2000, 2006, and 2010 are selected for interpretation and classification. Analysis of the types of desertification and land use reveals the temporal and spatial characteristics of five distinct time periods from 1985 to 2010. This study analyzes the current status of desertification in Nouakchott and suggests five preventive measures.

Key words: desertified land; progress of desertification; West Africa; combating desertification

1 Introduction

In recent years, global desertification has increasingly attracted attention from international organizations and researchers. Desertification has occurred not only in arid and semi-arid regions, but also in some humid and sub-humid areas (Zhu *et al.,* 1996), and it is particularly serious in the extreme arid Sahel region of Africa. The first desertification problem to cause worldwide concern was the result of the great drought that occurred in the 1960s and 1970s (Butzer *et al.,* 1983). The ecological environment of the African continent is clearly affected by global climate change. Observations over the last fifty years have shown significant increases in temperature over West Africa and the Sahel region, and, although there is a lack of comprehensive observational data for the continent of Africa as a whole, there have also been regional changes in rainfall (Sylla *et al.,* 2012; Kim *et al.,* 2013). Over parts of the western and eastern Sahel regions in Northern Africa, for which sufficient data are available, there have been likely decreases in annual precipitation over the past century (Niang *et al.,* 2014).

For many years, the limitations of water resources have seriously inhibited sustainable development of African countries, and, against a background of global climate change and population expansion, the issue of water resources has become more prominent. At present, more than 70% of African countries and regions face a crisis of shortages in water resources, with the lives of 300 million people being badly affected by the lack of water. Moreover, the desertification of land caused by water shortage and ecological deterioration is becoming an increasingly serious problem. Africa is one of the regions that is most severely affected by

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desertification, especially North Africa, Central Africa, and West Africa. Desertified land occupies more than about 66% of the total area of these regions, and they account for 50% of the world's desertified land. Over the past 30 years, there have been significant reductions in the areas of African grassland (reduced by 700 million hectares) and per capita arable land (more than 50% reduction), and, in particular, the area of forest has been halved (Wan, 1995), which poses a serious threat to the security of food supplies in Africa.

Mauritania is located in the Western Sahara: to the west is the North Atlantic, and it borders on Mali to the east, Senegal to the south, and Morocco and Algeria to the north (Fig. 1). The land area is 1.03×10^6 km^2, two-thirds of which is covered by the Sahara Desert. The remaining one-third is located at the edge of the desert, and is semi-desert, with a population of 3.28×10^6 and 3.75×10^6 hectares of arable land (CIA, 2017). Mauritania is not only one of the world's poorest countries, but also one of the most drought-prone countries in Africa, being known as the "Desert Republic." Its capital, Nouakchott, is located in the west of the country, 5 km from the Atlantic coast (Fig. 1). It is the country's largest city, with an area of 1000 km^2 (0.09% of the total land area). Because of its location, it has been threatened by both ocean and desert, with the threat of desertification being particularly pronounced. As early as the 1960s, even before the drought period began in 1968–1970, the periphery of Nouakchott was threatened by the invasion of aeolian sand. The action of wind erosion following water erosion led to the burial of highways by sand and a very significant desertification hazard (Mainguet *et al.,* 2003).

In addition to natural factors such as climate change, the impact of human activities, especially the rapid growth of the population, is one of the major factors accelerating desertification in the Sahel region. From 1950 to 2000, Mauritania's population increased from 800 000 to 2 700 000 (UNEP, 2002), with Nouakchott accounting for more than one-third of the national population. However, the area of fertile land decreased from 15 million hectares to 1 million hectares, and the proportion of desert and semi-desert increased from two-thirds of the total land area to more than 90% percent. The high population density, together with a grazing-dominated lifestyle, make the shortage of water resources more severe, with freshwater resources being extremely scarce. At present, the municipal water supply for Nouakchott comes from the South Water Transfer Project, and the food supply comes entirely from the southern cities of Mauritania. In order to save water, there is no farmland in Nouakchott itself.

In short, under the combined effects of climate and human activities, a series of serious problems have developed in the region of the capital, especially desertification, which has become a great obstacle to local development. Therefore, in the present study, Nouakchott is selected as a key area for an analysis using remote sensing data and GIS technology

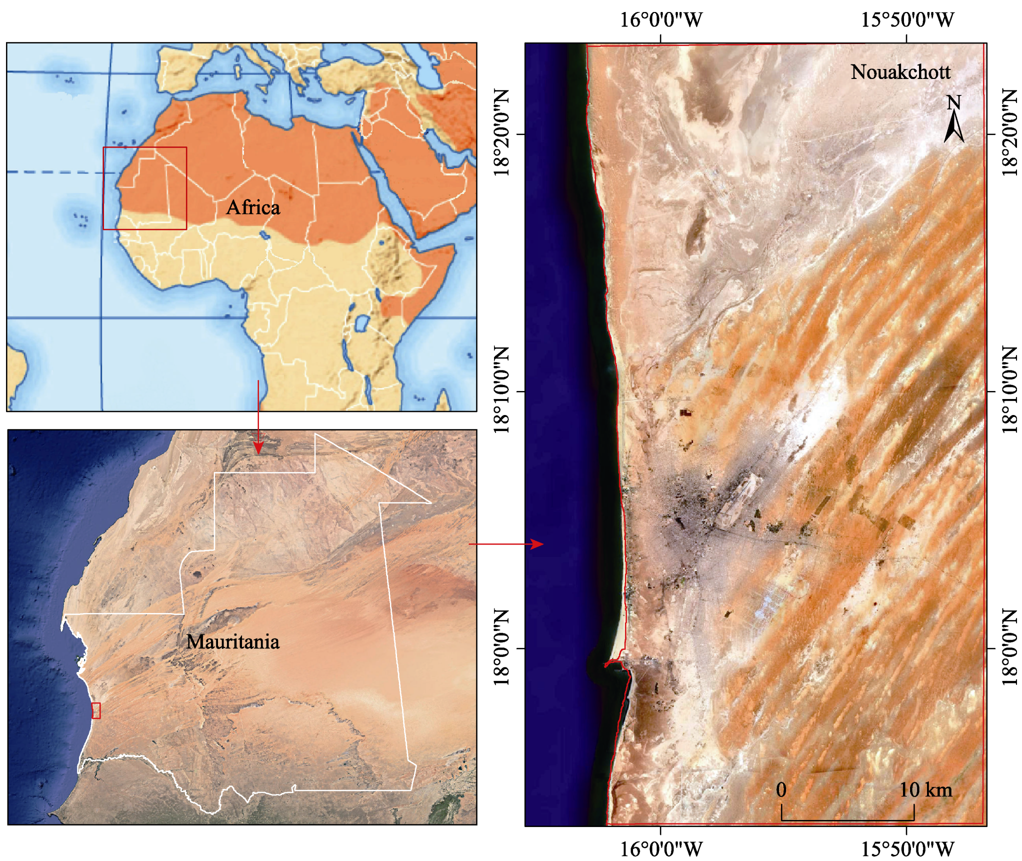

Fig.1 Maps showing the location of the area under study

to illustrate the dynamic characteristics of desertification. Appropriate measures are then proposed for controlling future desertification in the region. The results of this study not only provide basic data on desertification in the capital city, but also lay the basis for the development of a strategy to combat desertification, as a component of regional planning.

2 Materials and methods

2.1 Extraction of desertification information

At present, no general worldwide index system for the extraction of desertification information is available, not only because of differences in regional characteristics, but also because desertification of land is a complex ecological degradation process. In this age of high-speed information retrieval, it is not possible to extract desertification information from remote sensing data with sufficient precision using only a single index as the extraction standard. Therefore, on the basis of previous results (Tripathy *et al.,* 1996; Li and Zhang., 2003; Liu *et al.,* 2005; Niu, 2005; Zeng *et al.,* 2005; Sun *et al.,* 2005; Ma *et al.,* 2007; Han *et al.,* 2013), the following five indicators for extraction of desertification information were selected for this study: surface albedo (Albedo) (Liang *et al.,* 2003), modified soil-adjusted vegetation index (MSAVI) (Wang *et al.,* 2008), land surface temperature (LST) (Qin *et al.,* 2001), vegetation coverage (FVC), and temperature vegetation drought index (TVDI) (Cao *et al.,* 2008). These indicators have the following characteristics: a high degree of correlation, reliability, practicality, and easy image inversion. Liu Aixia (2005) used these five indices to extract desertification information from MODIS and NOAA low-resolution images, and found the accuracy and reliability of the results to be better than those with other combinations of indicators. In theory, with improved resolution of remote sensing images, the accuracy of the desertification information extraction results should be better than those from low-resolution data. Therefore, the five indicators selected in this study should be ideal for the extraction of desertification information from high-resolution remote sensing data, such as Landsat, TM, and ETM+.

In this study, the determination of desertified land and land use types was based on previous classification standards (Gao *et al.,* 2005; Chen *et al.,* 2007; Chang *et al.,* 2007; Zhao *et al.,* 2008), dune types (Zhu and Liu, 1981; Zhang *et al.,* 2010), and the characteristics of the study area, generally divided into desertified and non-desertified land. The desertified land was divided into four classes, namely, very severe desertification, severe desertification, moderate desertification, and light desertification, with the remaining land being classified as having no desertification. Land-use and land-cover types were divided into 10 classes: water bodies, sebkha, artificial green land, urban land, civil airports, roads, mobile dunes, semi-mobile dunes, semi-fixed dunes, and fixed dunes. This classification met the basic requirements for research on land-use and land-cover changes in the process of land desertification, and further allowed a characterization of the development of desertification in the study area.

In order to illustrate the dynamics of the development of desertification, data on five phases (represented by the years 1985, 1988, 2000, 2006, and 2010) were considered. The remote sensing data all came from the US Geological Survey (USGS) website. Other relevant data included administrative and land-use maps for the year 2000 at a scale of 1:1 000 000. Data preprocessing (atmospheric correction, geometric correction, and mosaic and projection transformations) was carried out using ENVI 5.3 software, and the UTM 28N projection and the WGS84 coordinate system were selected. The classification index system was determined as follows. First, data were obtained from two field studies and, after artificial visual interpretation, were combined with Google Earth high-resolution images to provide the training samples. A statistical analysis of these samples was then performed, histograms were obtained, and the cumulative frequency was determined. The threshold range between each class was determined, with five indicators in each period, and the TM/ETM+ desertification index system was established. As examples of this process, the classification standards for the years 2000 and 2010 are shown in Tables 1 and 2, respectively. Finally, each image was classified using a decision tree method. First, the five indices obtained from the inversion were synthesized, and a new multi-band image was generated as the initial image for decision tree classification. Then, typical training samples were selected for analysis of the characteristics of different types of desertified land and eigenvalue thresholds, and a stable relationship was established between the indicators and the types of desertified land. Thus, sample selection had a decisive influence on the decision tree classification. Typical samples were selected from a large total number of

Table 1 Index system for extraction of desertification information for the year 2000

Degree of desertification	Albedo	MSAVI	FVC	LST	TVDI
No desertification	<0.25	>0.29	>0.4	298–310	<0.64
Light	0.25–0.31	0.14–0.29	0.30–0.4	304–313	0.64–0.71
Moderate	0.31–0.35	0.12–0.14	0.30–0.20	306–313	0.71–0.77
Severe	0.35–0.38	0.10–0.12	0.155–0.20	308–310	0.77–0.84
Very severe	>0.40	<0.10	<0.155	309–313	>0.84

Table 2 Index system for extraction of desertification information for the year 2010

Degree of desertification	Albedo	MSAVI	FVC	LST	TVDI
No desertification	<0.2	>0.36	>0.5	295–310	<0.57
Light	0.20–0.27	0.22–0.36	0.35–0.5	304–311	0.57–0.64
Moderate	0.27–0.30	0.19–0.22	0.28–0.35	306–311	0.64–0.71
Severe	0.30–0.33	0.16–0.19	0.225–0.28	307–309	0.71–0.78
Very severe	>0.33	<0.16	<0.225	308–311	>0.78

samples, and the spectral characteristics of these selected samples were then analyzed. Different types of spectral features were found. Finally, based on expert knowledge, typical training samples were used to determine the decision tree classification threshold.

2.2 Analysis of accuracy

According to the classification results, the five indices can distinguish water, artificial vegetation, and sebkha well, but it is difficult to distinguish and extract data on urban land use or on the different types of desertified land with a single index. Even with five indicators, some areas could not be classified correctly. In this study, 1000 random reference points were collected as ground truth values from Google Earth high-resolution images. The overall classification accuracy and kappa coefficients of each image were obtained using a confusion matrix (Table 3).

Table 3 Statistics on accuracy of decision tree classification

Year		Desertified land				Non-desertified land		
		Very severe	Severe	Mod-erate	Light	Artificial green land	Urban-village land	
1985	PA	0.83	0.84	0.76	0.65	0.83	0.59	0.86
	UA	0.83	0.90	0.65	0.65	0.86	0.56	0.85
	OA				0.82			
	Kappa				0.79			
1988	PA	0.86	0.90	0.83	0.59	0.80	0.57	0.93
	UA	0.91	0.85	0.78	0.63	0.71	0.74	0.87
	OA				0.86			
	Kappa				0.83			
2000	PA	0.91	0.94	0.74	0.76	0.87	0.75	0.91
	UA	0.97	0.85	0.66	0.76	0.79	0.79	0.89
	OA				0.89			
	Kappa				0.87			
2006	PA	0.83	0.88	0.90	0.59	0.93	0.59	0.90
	UA	0.88	0.80	0.69	0.56	0.93	0.70	0.90
	OA				0.85			
	Kappa				0.82			
2010	PA	0.91	0.82	0.79	0.71	0.80	0.73	0.91
	UA	0.97	0.80	0.67	0.67	0.73	0.82	0.84
	OA				0.87			
	Kappa				0.84			

PA: producer's accuracy, the percentage of the number of pixels in the category when the classified land cover category corresponds to real ground reference data. The user does not know the truth map, so it is only possible to guess how reliable it is based on the results given by the classifier.
UA: user's accuracy, a checkpoint of a land cover category that belongs to a true ground reference, where some checkpoints are misclassified and the percentage of pixels is correctly classified. Producers know the truth maps, and they use classifiers to evaluate the classifier in proportion to the number of points in the truth graph.
OA: overall accuracy, the sum of correctly classified cells divided by the total number of pixels.

Table 3 shows that the producer's accuracy is between 0.57 and 0.94, with the classification accuracy of urban-village land being the lowest and that of the severely desertified land the highest. The user's accuracy is between 0.56 and 0.97, with the classification accuracy of the lightly desertified land being the lowest and that of the very severely desertified land the highest. Table 3 also shows that when the overall accuracy is higher, the error probability is smaller, and while the classification accuracy of urban land is low, its error probability is larger. In the results obtained from the actual classification, some of the urban and rural land is incorrectly classified as desertified land. The main reason for this is that because the capital city is located in a desert region, new residential buildings are located directly in the desert and the area of sandy land is relatively large in the less densely populated areas around the city. Therefore, in low-resolution images, the spectral characteristics of the pixels are similar to those of desertified land. Each of the extraction indicators of desertification is good at distinguishing between salt marsh and vegetation. However, they are not able to distinguish clearly among small areas of urban land and lightly or moderately desertified land, since these all have similar characteristics in terms of texture and vegetation cover.

3 Results and discussion

3.1 Temporal and spatial patterns of variation of desertification in different periods

3.1.1 Area variation of desertified land

Based on the classification of remote sensing images for the five years 1985, 1988, 2000, 2006, and 2010 (Fig. 2), the changes in desertification area for the different periods are shown in Table 4. The problem of desertification is clearly very serious, with desertified land and salt marsh accounting for more than 88% of the total land area of the region. Very severe and severe desertification accounted for more than 93% of the total area of desertified land, with moderate and light desertification only making up a few percent. In general, the area of very severe desertification reached its maximum in 2000, with an increasing trend from 1985 to 2000 but a decreasing trend from 2000 to 2010. In contrast, moderate and severe desertification both showed a decreasing trend from 1985 to 2000 and an increasing trend from 2000 to 2010. For light desertification, there was a decreasing trend across the entire study period from 1985 to 2010. In non-desertified land, urban land and artificial green land both showed an increasing trend from 1985 to 2000, which is closely related to the process of urbanization, with Nouakchott undergoing a rapid development stage during these 15 years. Nouakchott is close to the Atlantic, so the changes in the area of sebkha due to the effects of sea water exhibit a similar trend to the area of severe desertification.

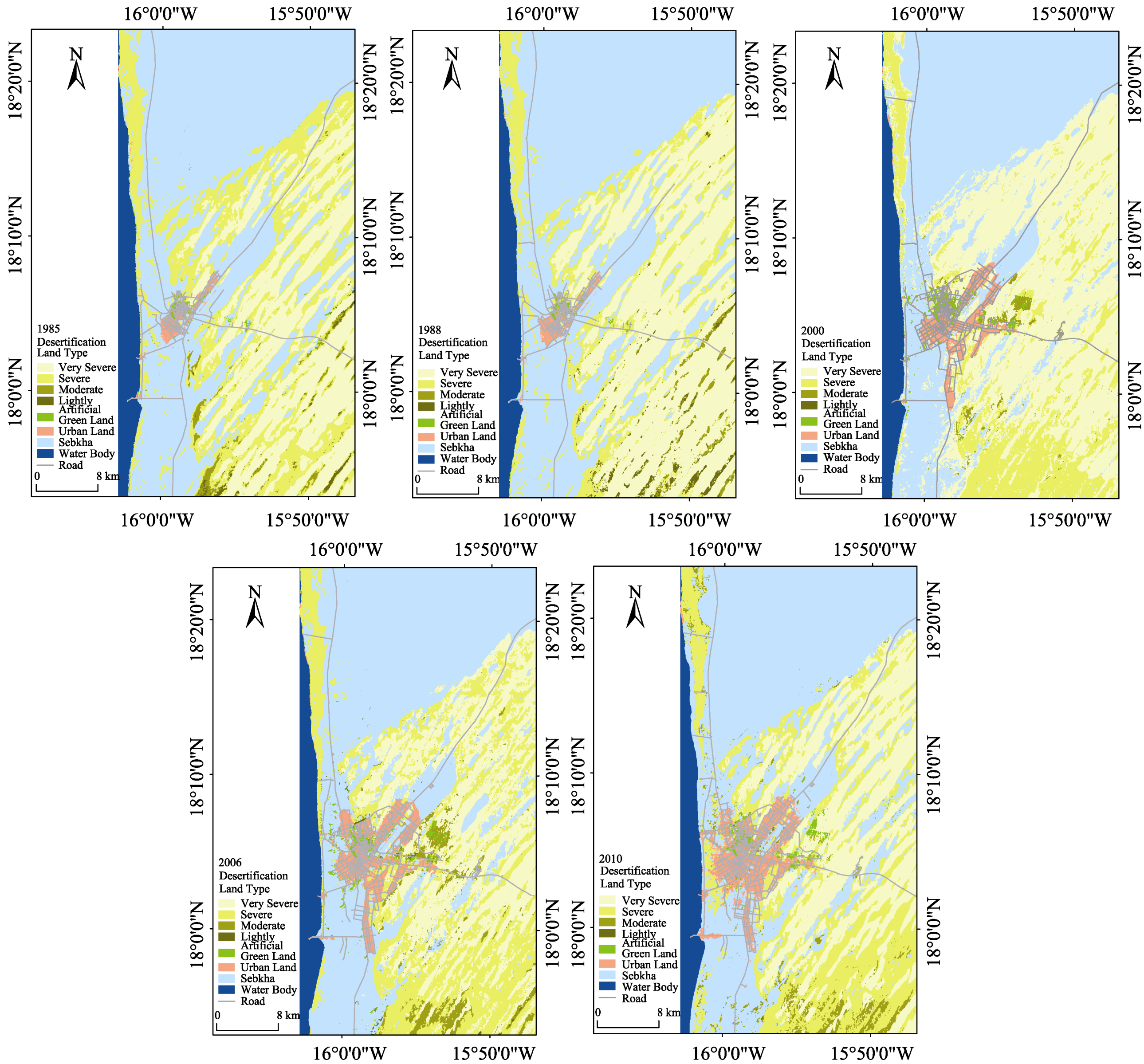

Fig.2 Sandy desertification levels in Nouakchott from 1985 to 2010

Table 4 Land areas (in km^2) of different degrees of desertification from 1985 to 2010

Type		1985		1988		2000		2006		2010	
		Area	Ratio(%)	Area	Ratio(%)	Area	Ratio(%)	Area	Ratio(%)	Area	Ratio(%)
Very severe		346.92	22.13	474.72	30.28	584.61	37.29	338.62	21.60	335.04	21.31
Severe		378.30	24.13	245.00	15.63	239.80	15.30	378.20	24.12	352.60	22.43
Moderate		25.03	1.60	24.65	1.57	16.51	1.05	50.20	3.20	50.45	3.21
Light		4.07	0.26	14.47	0.92	0.03	0.00	2.52	0.16	0.19	0.01
Non-desertified land	Artificial green land	11.49	0.73	8.18	0.52	23.35	1.49	24.57	1.57	26.99	1.72
	Urban land	12.07	0.77	13.81	0.88	43.15	2.75	58.49	3.73	73.58	4.68
	Sebkha	700.40	44.68	697.50	44.49	570.90	36.42	624.90	39.86	639.40	40.79
	Water	89.42	5.70	89.37	5.70	89.35	5.70	90.20	5.75	89.45	5.71

3.1.2 Changes in the spatial distribution of desertified land

The types of changes can be divided into five classes: unchanged land, reduced desertification, artificially reduced desertification, increased desertification, and other types of land changes (Table 5). Table 6 shows that from 1985 to 2000, 1057.46 km^2 of land did not change, while the area of

Table 5 Land change types of desertified land

Type of change	Rule	Number
No change	No change in any kind of land	1
Reduced desertification	Mobile dunes → semi-fixed dunes, semi-mobile dunes, and fixed dunes Semi-mobile dunes → semi-fixed dunes and fixed dunes Semi-fixed dunes → fixed dunes	2
Artificially reduced desertification	Mobile dunes → artificial green land and urban land Semi-mobile dunes → artificial green land and urban land Semi-fixed dunes → artificial green land and urban land Fixed dunes → artificial green land and urban land Sebkha → artificial green land and urban land	3
Increased desertification	Semi-mobile dunes → mobile dunes Semi mobile dunes → mobile dunes and semi-mobile dunes Fixed dunes → Mobile dunes, semi-mobile dunes, and semi-fixed dunes Artificial green land → mobile dunes, semi-fixed dunes, semi-mobile dunes, fixed dunes, and sebkha Urban land → mobile dunes, semi-fixed dunes, semi-mobile dunes, fixed dunes, and sebkha Sebkha → mobile dunes, semi-fixed dunes, semi-mobile dunes, and fixed dunes	4
Others	Other transformation types	5

Table 6 Variation of area of sandy desertified land changes during different periods (km^2)

Type of change	1985–2000	2000–2010	1985–2010
1	1057.46	1102.59	1154.02
2	84.07	205.25	107.34
3	48.32	37.78	76.39
4	355.09	91.10	164.06
5	22.79	130.99	65.91

desertified land was 404.47 km^2; and from 2000 to 2010, 1102.59 km^2 of land did not change, while the area of desertified land was 367.59 km^2. Fig. 3 shows that from 1985 to 2000, there were reversals of desertification around the urban area and in the southeast region. In the first case, this was due to expansion of the city and a project for protecting the capital through direct transformation of desertified land into non-desertified land. The second case represents transformation among different types of desertified land. There was also a reversal of desertification around the city from 2000 to 2010, but this was less dramatic compared with the changes from 1985 to 2000. Other changes in areas of desertification were mostly distributed in the northeast and southeast of the city, mainly resulting from transformations among different types of desertification. From the spatial distributions of desertification in 1985–2000 and 2000–2010, it can clearly be seen that the degree of desertification decreased in the northeast during 1985–2000 and increased in the southeast during 2000–2010. These changes were possibly due to human activity. From field surveys, we found that a lack of water resources forced the inhabitants of the northern region to migrate south. This migration process was accompanied by overgrazing by livestock, and the consequent serious damage to vegetation cover led to the movement of originally fixed sand and sand dunes, resulting in a gradual increase in desertification.

3.1.3 Spatial distribution characteristics of desertified land

Table 7 and Fig. 4 show the results of the monitoring of different types of desertified land in Nouakchott in 2010. The monitoring area was 1567.70 km^2, of which the area of desertification was 738.78 km^2. Nouakchott includes the following nine administrative divisions: KSAR (KR), SEBKHA (SA), RIADH (RH), EL MINA (EA), ARAFAT (AT), DAR NAIM (DM), TOUJOUNINE (TE), TEYARET (TT), and TEVRAGH ZEINA (TA). From the test results, the capital city can be divided into two areas: a centralized distribution of heavy desertification in the east and northeast, and a zone of development of severe desertification in the south.

The first of these involves the four regions of KR, TT, DM, and TE, with a total area of 898.15 km^2. The area of very severe desertification is 266.56 km^2, making up 79.45% of the total of very severely desertified land area in Nouakchott. The main characteristic of this area is the presence of highly mobile dunes scattered throughout sandy land. In the northeast, TE suffers from the most very severe desertification, which is very unfavorable for the development of this area of the capital city.

There is also severe desertification in the west and southwest of Nouakchott, accompanied by moderate desertification in the RIADH area. The areas of severe and very severe desertification are 140.3 km^2 and 67.86 km^2, respectively. Semi-fixed dunes and sand ridges are found mainly in the northwest of the city. There is a large human population on the tall ridges between dunes, while shrubs and small trees are distributed on the leeward slopes of the dunes. Because the vegetation cover in this area is greater

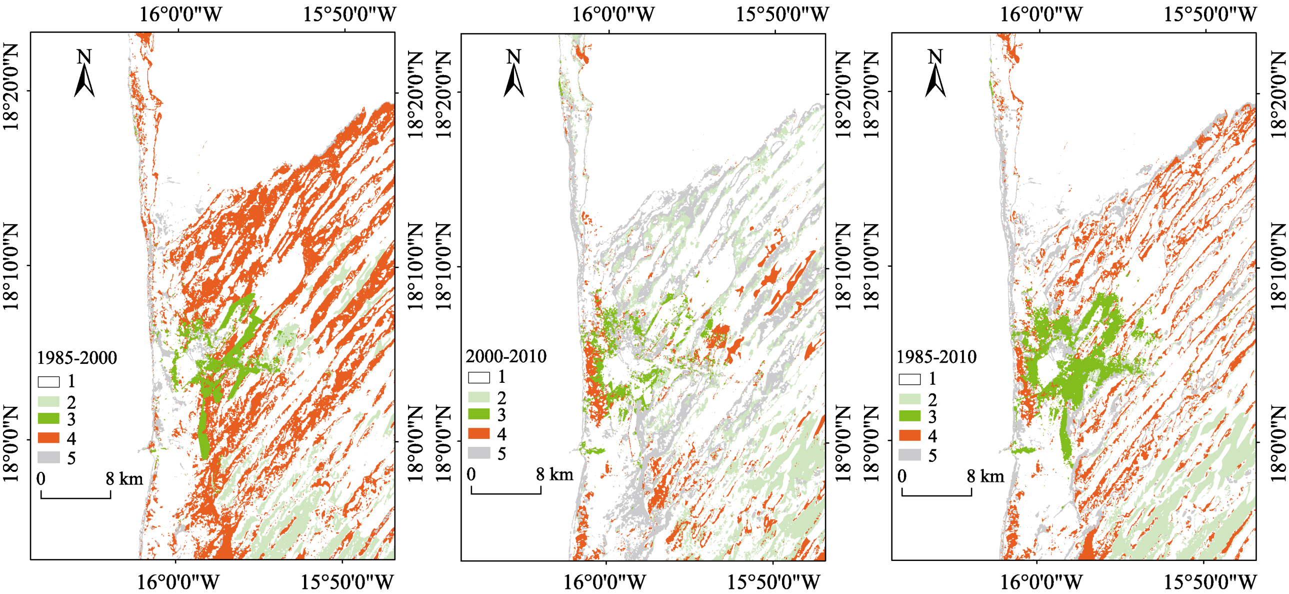

Fig.3 Distribution of variations in sandy desertified land changes during different periods

Table 7 Land area of various degrees of desertification in Nouakchott in 2010 (km^2)

Monitoring region	Monitoring area	Very severe	Severe	Moderate	Light	Artificial green land	Urban land	Sebkha	Water bodies	Sort
KR	218.63	13.36	17.41	1.02	0.00	1.92	8.82	176.10	0.00	6
SA	12.36	0.00	4.42	0.11	0.01	0.60	5.39	1.65	0.19	8
RH	288.33	67.86	140.30	33.51	0.04	0.03	5.22	41.36	0.00	1
EA	105.00	0.00	13.68	3.33	0.02	1.46	14.57	69.98	1.96	7
AT	15.95	0.03	3.82	0.03	0.01	0.25	11.20	0.61	0.00	9
DM	112.84	44.60	26.27	1.26	0.06	1.85	10.53	28.28	0.00	4
TE	290.93	163.20	75.58	1.34	0.00	9.38	4.34	37.09	0.00	2
TT	275.74	45.40	28.86	1.27	0.00	0.29	2.92	197.00	0.00	3
TA	160.95	1.06	42.30	8.58	0.04	6.20	10.53	91.33	0.92	5
Water	86.97	0.00	0.05	0.00	0.00	0.02	0.06	0.45	86.39	—
Total	1567.7	335.5	352.68	50.45	0.19	21.99	73.58	643.85	89.45	

than that in the northern area, some herdsmen have settled and allowed their animals to graze in these sandy lands, with the result that the fixed and semi-fixed dunes have become dangerous moving dunes.

3.2 Strategy for combating desertification

Overall, areas around the city are densely covered by sand dunes, which severely impact the daily lives of the city's inhabitants. For example, the dunes have already buried houses in the suburbs and are now moving toward the center of the city. In recent years, the city has continually been subjected to sandstorms, which often cover main roads, streets, and alleys by huge amount of sand. The arena of the Olympic Stadium in Nouakchott has already been swallowed by sand dunes. In order to combat desertification and improve the capital's ecological environment and living conditions, Mauritania has taken a series of protective and control measures, including the launch of the Greenbelt Project and the Program for Restoration and Promotion of Greenbelt Works of Nouakchott (Fig. 5 and Photo 1). A sand stabilization and vegetation rehabilitation project has been conducted around the capital to the north and east. Although this project has been underway for the past 40 years, sandstorms remain a threat to the existence of the capital city.

3.2.1 Current status of construction and maintenance of the project for the protection of Nouakchott

Based on observations made during the site survey and an analysis of relevant data, we believe that the current status of construction and maintenance of the project for protecting Mauritania's capital can be summarized as follows:

A. Through years of implementation of works such as dune fixation, afforestation, and rehabilitation of natural vegetation via manual enclosures, a sand-blocking and dune-fixation protection belt around Nouakchott has taken

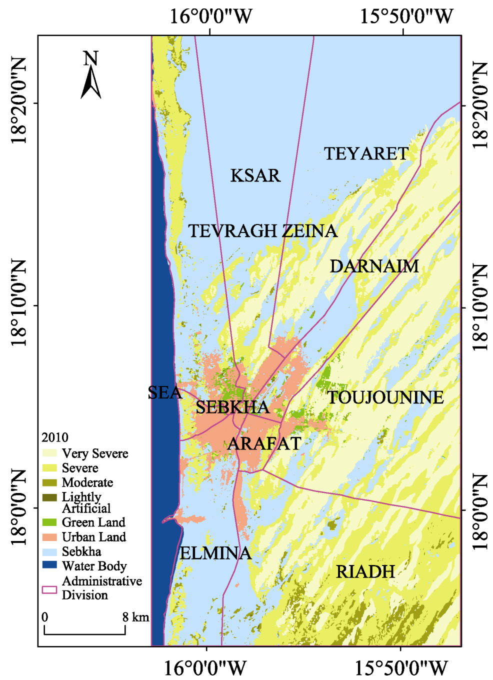

Fig. 4 Distribution of sandy desertification in Nouakchott in 2010

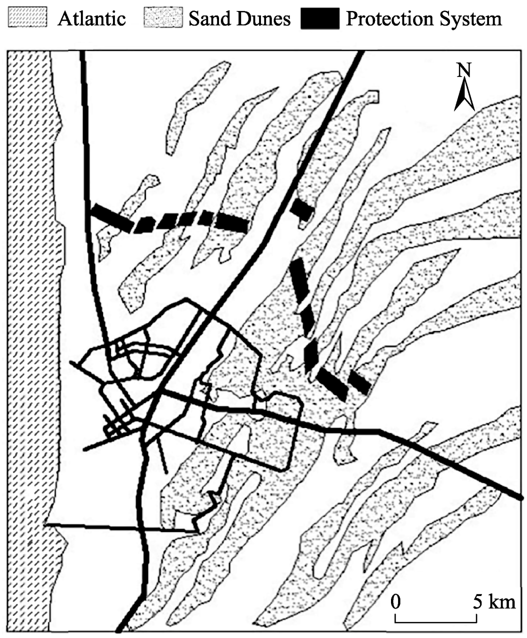

Fig.5 Sketch map of the current Capital Circle Protection Project system of Nouakchott

Photot 1 Current situation of the Capital Circle Protection Project

its initial shape. It has played an important role in facilitating ecological development around the capital, and reducing the number and intensity of sandstorms attacking the city.

B. Large dune-fixation lattices, constructed using materials such as tree branches, suffer severely from wind erosion and sand burial in areas of drifting sand dunes and sand ridges, but have been well preserved in the areas between ridges.

C. Manual afforestation efforts in areas of sand dunes and sand ridges have delivered good results. The saplings that were planted have grown well, and maintained high survival and preservation rates (generally from 60% to 70%), although they did suffer from wind erosion and sand burial at an early stage. Shrubs can now be seen in areas where afforestation was conducted early, delivering sound wind-proofing and dune fixation. However, the survival rate of saplings manually planted on the flat grounds among sand dunes has been low (generally less than 20%).

D. Natural vegetation on flat areas among sand dunes and sand ridges has shown sound recovery, under the protection of dune-fixation barriers and wire netting, and a vegetation cover of 30–60％ has been achieved.

3.2.2 Main problems of the Capital Circle Protection Project

A. The Capital Circle Protection Project has suffered from a lack of systematic and comprehensive planning. Although dune-fixation and vegetation-recovery measures have been taken around the capital, two main problems remain: 1) Sand flow, sand dunes, and sand ridges are still moving toward the urban area because the protective measures encircling the capital have not formed a closed system; and 2) A large number of drifting sand dunes still remain between the protective circle and the city, continuing to jeopardize the latter, and the buildings and roads of the city are still under threat due to the intrusion of the drifting sand.

B. The usefulness of the mechanical lattices is not clear. These are temporary dune-fixation measures, constructed rapidly with the aim of obtaining immediate results. Although many large dune-fixation mechanical lattices (35 m× 35 m) have been constructed in the protection project around the capital, they cannot play a fully effective role in dune fixation in the area of drifting dunes owing to its wide extent. Those arranged on the flat ground among sand dunes are also not fully effective, because there is almost no drifting sand in these areas.

C. Saplings planted on some drifting dunes and sand ridges have suffered severely from wind erosion and sand burial, resulting in a low survival rate. Because the mechanical lattices arranged in the drifting desert area have large dimensions, plants raised within them cannot be given sufficient protection and suffer severely from wind erosion and sand burial, with a consequently low survival rate.

D. Only a narrow range of plant species have been adopted for forest plantation and vegetation recovery, with consequent poor results. In particular, there is a lack of small bushes and herbaceous plants.

3.2.3 Planned scheme for rehabilitation of the comprehensive protection system around the capital city

The only way for Mauritania to change the current situation in which its capital city is threatened by sandstorms, and to ensure that the city will not be buried by sand, is to rehabilitate and optimize the Capital Circle Protection Project and construct a comprehensive protection system around the city. A plan for rehabilitating the protection system around Nouakchott has been prepared based on an understanding of the current threat posed by sandstorms and on assessment of the existing problems with the Capital Circle Protection Project, together with China's experiences in sand prevention and control over many years (Lei *et al.*, 2008; Li *et al.*, 2008; Xie *et al.*,2015a, 2016b), in combination with considerations of the social, economic, and resource status of Mauritania.

The general layout of the comprehensive protection system around the capital is as follows. A five-in-one comprehensive protection system (Fig. 6) is to be established from inner to outer areas in accordance with the current status of the sandstorm hazard and environmental conditions and guided by planning considerations:

A. **A sand-clearing and dune-fixation area in the city,** where drifting sand will be cleared, hardened, or covered by vegetation to eradicate drifting sand from the city and to improve and beautify the urban environment.

B. **An ecological and economic barrier belt** with a width of 2000–3000 m will be established through diversion irrigation in the suburban area. According to the current status of this plan, forest plantation and vegetation recovery supported by natural rainfall is unable to thoroughly protect the capital from sandstorms or to sufficiently change ecological and living conditions such that the ecological safety of the capital can be ensured. This barrier will be composed of a 200 m-wide basic sand-blocking and windproof forest belt with trees, bushes, and grasslands as a final barrier to block the intrusion of drifting sand together with an ecological and economic forest belt. Tall trees will be planted to produce a protective forest network in which ecological and economic plants and vegetables will be planted to develop ecological agriculture and establish a subsidiary food base for the capital. The drifting desert in the suburbs will be fixed by diversion irrigation and establishing an ecological and economic protection system. Grazing activities in the suburbs will be prohibited to improve the living conditions of the people living there, change their methods of production and life style, and turn them into ecological industry workers. The development of this area will not only thoroughly change the ecological environment of the capital, but also make it a vegetable and subsidiary food base for the capital. At the same time, a large number of employment opportunities will be created.

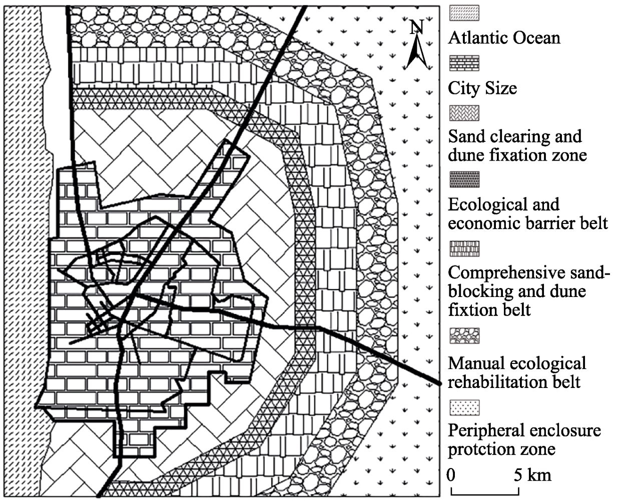

Fig.6 Layout of the planned comprehensive protection system in Nouakchott

C. **A comprehensive sand-blocking and dune-fixation belt** with a width of 1000 m will be established outside the ecological and economic belt by combining mechanical dune-fixation lattices with manual plantation to block and fix drifting sand within the belt.

D. **A manual ecological rehabilitation belt** with a width of 3000–5000 m will be established outside the sand-blocking and dune-fixation belt by planting vegetation.

E. **A peripheral enclosure protection zone** in which grazing is prohibited will be established within 5000 m outside the ecological rehabilitation belt around the capital.

4 Conclusions

In this study, high-resolution remote sensing images of Nouakchott obtained during the years 1985, 1988, 2000, 2006, and 2010 have been selected for interpretation and classification. By analyzing types of desertification and land use, we have revealed the temporal and spatial characteristics of the five periods from 1985 to 2010. The results show that there was a change in the trend of desertification in 2000. Specifically, desertification was in a phase of positive development from 1985 to 2000, which was reversed from 2000 to 2010. This transformation was most prominent in areas of very severe and severe desertification. In normal regions, the areas of urban land and artificial green land have shown positive growth trends. In terms of spatial distribution, the areas showing a reversal of desertification are located mainly in the southeastern parts of the city, while increased desertification has occurred mainly in the southeastern and northeastern parts. Taking account of the current status of desertification, and with the aim of overcoming the defects and deficiencies of the original protection system, a new protection scheme has been proposed. According to this proposal, a five-in-one comprehensive protection system around the capital city should be established from the inner to the outer areas, in accordance with the current status of the sandstorm hazards and environmental conditions, and guided by judicious planning considerations.

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毛里塔尼亚首都圈荒漠化现状及其防治规划

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摘　要：毛里塔尼亚坐落于撒哈拉沙漠西部，是非洲最不发达的国家之一，其首都努瓦克肖特拥有全国 23%的人口，同时遭受撒哈拉沙漠的侵蚀和大西洋海水的倒灌。受气候变化和社会经济因素的共同影响，荒漠化成为当地人民生存的最大威胁。本研究通过对 1985 年，1988 年，2000 年，2006 年和 2010 年五期努瓦克肖特的 TM 影像进行解释和分类，得到不同时期荒漠化类型及其时空分布特征，揭示了努瓦克肖特目前的荒漠化现状，并针对该研究区的荒漠化问题提出了防治规划和五项治理措施。

关键词：荒漠化土地；荒漠化进程；西非；荒漠化防治