

RESEARCH ARTICLE

Ecological security evaluation of Africa

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Abstract Africa, the second largest continent in the world, has achieved remarkable economic and political results through exploration and positive development. Ecological security comprehensively reflects the health and integrity of an ecosystem, and it is broadly defined as the security state of a complex artificial ecosystem composed of natural, economic and social factors. Ecological security determines the potential for sustainable development in Africa, especially with its rapidly developing economies. However, there is a lack of information on the ecological security state of the continent as a whole. In this study, we constructed an evaluation system based on a pressure-state-response model and evaluated the ecological security state of all 54 African countries. The results showed that, at the national level, the ecological security state of the countries in Africa differed, as did their spatial and temporal variations from 1995 to 2016. In general, African countries showed relatively good ecological security. The years 2007 and 2001 were the worst and best years, respectively, in terms of ecological security during the study period. At the regional level, North Africa and West Africa had the best and worst ecological security, respectively.

Keywords Africa, ecological security, evaluation system, PSR model

1 Introduction

Africa, the second largest continent in the world, has vast lands and diverse cultures, but has the lowest economic development of all the continents. Indeed, the vast majority of African countries are still developing^[1]. More than 75% of developing countries in the world are in Africa, and the ten least developed countries are all in Africa^[2,3]. In recent

years, however, Africa has achieved remarkable economic and political results through exploration and positive development^[4–6], and it is gradually shedding its underdeveloped image. The recent press reports indicate that African countries are at a stage of active exploration, looking for a suitable way to develop^[7,8]. In tandem with political achievements, economies in Africa are showing encouraging trends^[9]. Many problems remain, however, such as a fast-growing population^[10,11], food shortages, and environmental deterioration, and these problems have slowed development across Africa. Studies have shown that environmental conditions in most areas cannot be restored, a situation that stifles local economies^[12,13].

Ecological security is a comprehensive reflection of the health and integrity of an ecosystems^[14–16]. A definition of the concept was first proposed by the International Institute of Applied Systems Analysis^[17]. Discussion over this definition has been ongoing, although the generally accepted definition of ecological security includes two levels: a broad sense and a narrow sense^[14,15,18]. Broadly, a high level of ecological security denotes a region that is not threatened in terms of human life, health, basic rights, sources of life, necessary resources, social order, and the human ability to adapt to environmental changes^[17]. In other words, it is defined as the security state of a complex artificial ecosystem composed of natural, economic, and social factors^[15,19,20]. Corresponding to this, ecological security in the narrow sense refers to the security state of simple ecosystems consisting of natural and semi-natural ecosystems^[14,15].

Based on these definitions, scholars have offered multifaceted research directions that adopt different meanings of ecological security. Depending on the emphasis of such research, the definition of ecological security can be divided into two types. One type focuses on the structure and function of ecosystems^[21]. According to the basic principles of ecology, ecological security means that the natural environment meets the requirements for the survival and development of organisms within the system while withstanding external threats and injuries^[22,23]. The

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second type emphasizes ecosystem services and the impact on humans, such as the capacity of an ecosystem to support social politics and economies^[19,24–29].

Ecological security determines the potential for sustainable development in Africa, where economies are developing rapidly^[30]. Given economic globalization and close relations among countries in the world, it is important to understand the current ecological security state^[31,32]. However, there are few studies of the ecological security of African countries. Yang^[33] evaluated the ecological security of 11 countries along the Nile River. The results showed that, although ecological security has improved in all countries along the Nile with the exception of Sudan, the ecological security index fluctuated greatly and was slightly above 0.50. In the countries studied, the state of ecological security was not viewed optimistically.

In this study, in view of the current ecological security state in African countries, numerous indicators were selected and a reasonable evaluation model was used to quantitatively characterize the ecological security of all 54 countries in Africa. We anticipate that our results will provide a scientific basis for improving ecological security in Africa, and offer recommendations for facilitating international communication and cooperation in the future.

2 Study area and methods

2.1 Study area

The African continent comprises 54 countries and with its adjacent islands covers a total area of 3.02×10^7 km², accounting for about 20% of total global land area. The equator traverses the continent, and many countries are located between the Tropics of Cancer and Capricorn.

On the basis of international geographic division practices, the continent can be divided into five regions: North Africa, West Africa, East Africa, Central Africa and Southern Africa. The physical geography and level of economic development differs considerably among these regions.

2.2 Study methods

2.2.1 Ecological security evaluation system

A scientific and effective evaluation method is needed to establish a framework for evaluating ecological security state^[16]. The pressure-state-response (PSR) model is widely used in various fields^[34,35], and divides the evaluation object into three parts: pressure, state and response.

Based on the PSR model, existing research on ecological security and the current situation of African countries^[36–39], we selected 26 indicators to construct an evaluation system (Fig. 1). The pressure (P) was

established from 10 indicators of economic development and population. The state (S) was established from 7 indicators of land, atmosphere and water, and the response (R) was established from 9 social indicators. Indicators are either positive or negative depending on how they affect ecological security and positive indicators with higher value contribute more to ecological security, and vice versa.

2.2.2 Data processing

Each indicator in the evaluation system has a different unit and different dimensions. Thus, we normalized the original data from each indicator before performing calculations that converted the information into abstract data without units. Positive and negative indicators differed as follows: Positive indicator:

$$D_{ij} = (X_{ij} - \min X_j) / (\max X_j - \min X_j) \quad (1)$$

Negative indicator:

$$D_{ij} = (\max X_j - X_{ij}) / (\max X_j - \min X_j) \quad (2)$$

where X_{ij} and D_{ij} denote the original data and the normalized data, respectively, and $\max X_j$ and $\min X_j$ are the maximum and minimum values of j th indicator.

2.2.3 Indicator weight calculation

To calculate the weight of each indicator, we adopted the coefficient of variation (CV). The CV method is often used to compare differences between data sets. Each indicator has a different degree of variation, and it is given a corresponding weight:

$$A_j = S_j / M_j \quad (3)$$

$$W_j = A_j / \sum_{j=1}^n A_j \quad (4)$$

where A_j , S_j , M_j , and W_j are the coefficient of variation, mean variance, mean value, and weight of j th indicator, respectively.

2.2.4 Ecological security index calculation

Following the above data processing steps, the standardized indicator values and their weights were obtained. Based on these, we calculated the pressure index (P), state index (S), and response index (R), as follows:

$$P = \sum_{j=1}^n W_j \times D_{ij} \quad (5)$$

$$S = \sum_{j=1}^n W_j \times D_{ij} \quad (6)$$

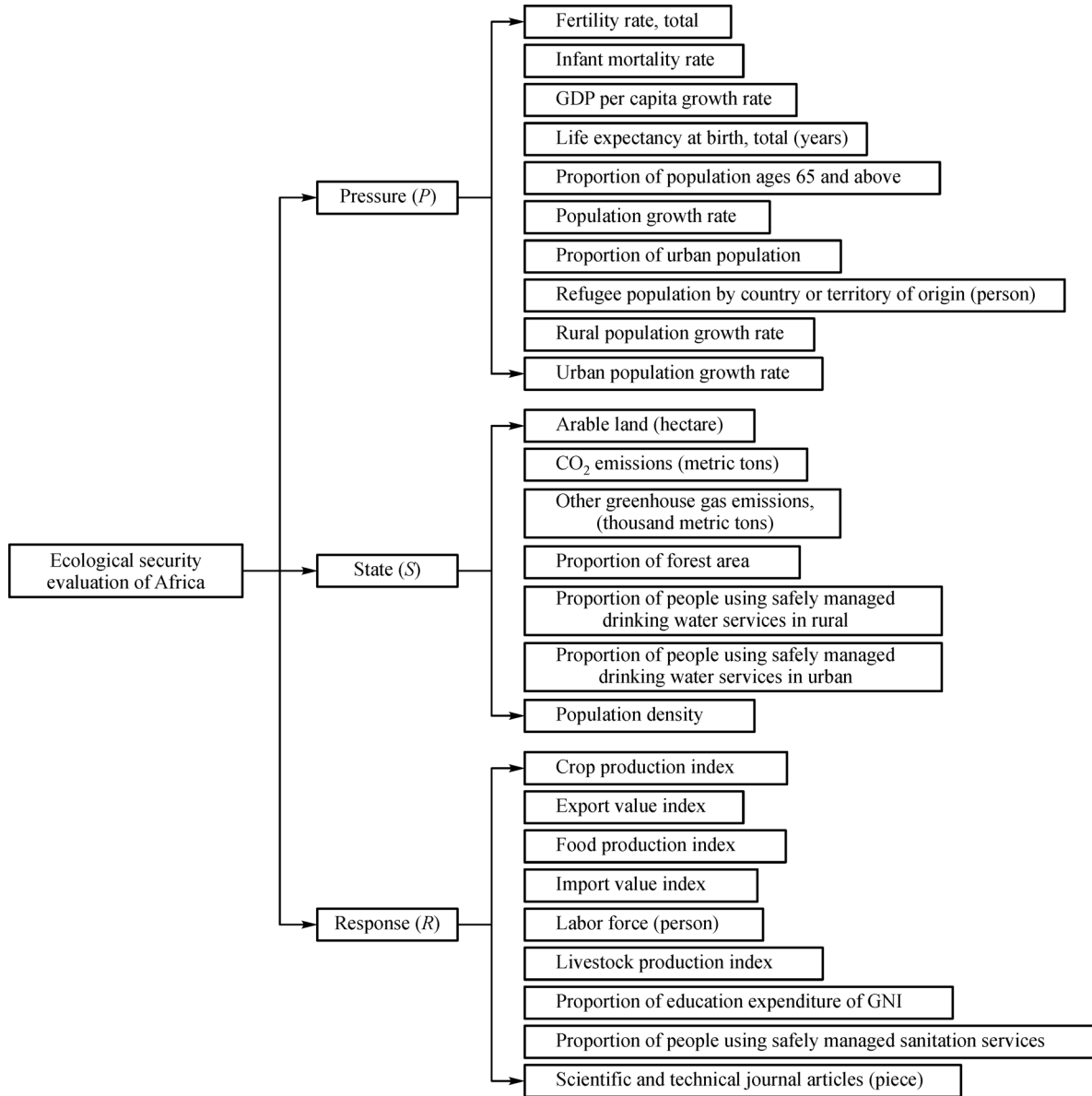


Fig. 1 Ecological security evaluation system for Africa. The first column is the target layer; the second column is the project layer: pressure (*P*), state (*S*), and response (*R*); the third column is indicator layer, with 26 indicators. Based on the influence of indicator value, the results were divided into positive indicators and negative indicators. All the indicators of the pressure layer, CO₂ emissions (metric tons), other greenhouse gas emissions (thousand metric tons) and population density in the state layer and the export value index and import value index in the response layer were negative, all others indicators were positive. The indicator, other greenhouse gas emissions, is consists of three gases: HFC (hydrofluorocarbons), PFC (perfluorocarbons), and SF₆ (sulfur hexafluoride). GDP: gross domestic product; GNI: gross national income.

$$R = \sum_{j=1}^n W_j \times D_{ij} \quad (7)$$

Finally, the ecological security index (*C*) is the sum of these three indices:

$$C = P + S + R \quad (8)$$

2.2.5 Ecological security classification standards

Currently, there are no definitive classification standards for ecological security^[13], and indeed there is relatively little research on the ecological security of Africa. Therefore, we adopted a detailed Chinese study of classification standards^[40,41] and combined it with research on the current situation in Africa^[33].

Based on the accuracy of evaluation results, ecological security state is divided into five levels. Level I is an extremely unsafe state and any country at this level is in a very poor and dangerous state of ecological security; Level II is an unsafe state and indicates that the country's ecological security is poor and needs to be improved in a timely manner; Level III designates a country in the middle, in a critical state of safety; Level IV indicates that the country is in a good ecological security state and has great development potential; Level V represents a safe state and indicates that the ecological security state is very good and suitable for humans to live^[42].

The whole value range is 0–1, so 0.50 can be taken as the boundary between good and poor ecological security. Due to the large differences in environment, economic and political development and obvious polarization among African countries, these classifications are not evenly spaced, and the numerical range of levels I and V is large. Levels II and IV are intermediate between a critical safety state, extremely unsafe state, and a safe state, respectively, so they have the same range. The classification standard for ecological security in African countries is shown in Table 1.

2.2.6 Data sources

The list of African countries and their division into five geographical regions were derived from the UN Economic and Social Council. Data from the World Bank Group for 1995–2016 was used to calculate the ecological security index. National GDP data in 2017 were obtained from International Monetary Fund.

Table 1 Classification standard of ecological security

| Level | C value | State |
|-------|-----------|------------------|
| I | 0–0.29 | Extremely unsafe |
| II | 0.30–0.44 | Unsafe |
| III | 0.45–0.49 | Critical safe |
| IV | 0.50–0.64 | Relatively safe |
| V | 0.65–1.00 | Safe |

3 Results and discussion

3.1 Ecological security index variations in Africa (1995–2016)

3.1.1 Variations in the ecological security index in North Africa

The results for countries in North Africa varied significantly (Fig. 2). Variation in North Africa was concentrated in Sudan during the study period. Ecological security in Algeria, Mauritania and Morocco increased from 1995 to 1998, although there was relatively little change. Libya remained the lowest in this region, and the values for Algeria and Egypt were high.

In numeric terms, the ecological security index was above 0.65 in most countries and has remained so for a considerable time. Algeria, Egypt and Morocco were relatively stable in terms of ecological security. Although they showed some fluctuation, the range of this fluctuation was not large. Egypt had an ecological security index of 0.88 in 2004, and this decreased from 2007 to 2013, after

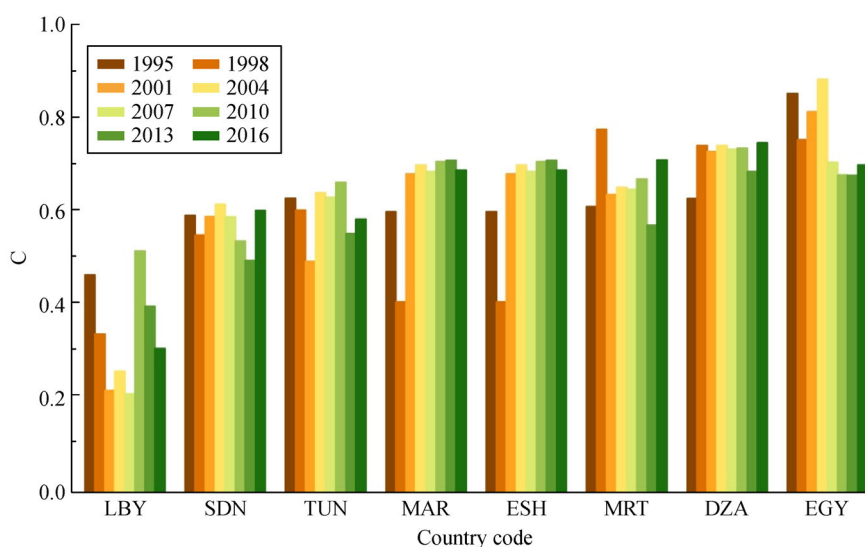


Fig. 2 Variations in ecological security index in North Africa. C is the ecological security index, and the value reflects the state of ecological security, 0.0 and 1.0 indicated the worst and the best, respectively. Country code is abbreviated country name. LBY, Libya; SDN, Sudan; TUN, Tunisia; MAR, Morocco; ESH, Western Sahara; MRT, Mauritania; DZA, Algeria; EGY, Egypt.

which it increased to 0.69 by 2016. The ecological security index for Algeria and Morocco remained around 0.70, although it was 0.62 and 0.59 in 1995, respectively. Mauritania showed almost no fluctuation from 2001 to 2010 but decreased to 0.57 and increased to 0.71 in 2013 and 2016, respectively. Sudan and Tunisia had an index of 0.50–0.65, which is relatively safe.

3.1.2 Variations in the ecological security index in West Africa

Gambia and Guinea-Bissau had extremely low ecological security, below 0.30 throughout the study period (Fig. 3) with an average value of 0.29 and 0.23, respectively. The index for Senegal changed significantly throughout the period. Indeed, Senegal is especially unstable, and it has poor ecological security. During the study period, the initial and final indices differed only slightly in Sierra Leone, at 0.54 in 1995 and 0.57 in 2016. There was a brief decline from 2001 to 2007, and its minimum was 0.32 in 2007. Nigeria had the best ecological security state in West Africa. In 2004, the index declined to 0.63, but it was otherwise above 0.70. After 2004, the value increased to 0.92 in 2016. The indices of the remaining 10 countries fluctuated, but they were relatively safe, ranging between 0.50 and 0.65. As such, the ecological security state in West Africa was relatively good.

3.1.3 Variations in the ecological security index in East Africa

East Africa consists of 17 countries, and in 70% of them

the ecological security was typically above 0.50 (Fig. 4). Given the large number of countries involved, variation in ecological security index in East African countries is complex, and each country has unique characteristics. Even in countries with the same ecological security there was marked interannual variation. For example, Madagascar and South Sudan are among the least developed countries in the world and changes to their ecological security was consistent. They remained below 0.45, dropping to 0.30 in 2010 in Madagascar. The index for Mauritius was 0.81 in 1995, the highest in the study period. Then, it declined to varying degrees over the next few years. In 2010, it reached its lowest level, at 0.55, but it was otherwise above 0.65 and Mauritius had the best ecological security in East Africa.

3.1.4 Variations in the ecological security index in Central Africa

Like Gambia and Guinea-Bissau, ecological security in the Central African Republic was extremely low, at less than 0.30 throughout the study period (Fig. 5). The value changed little, suggesting a lack of optimism concerning the future ecological security of the country. Equatorial Guinea had the largest variation in Central Africa with maximum and minimum values of 0.72 in 1995 and 0.30 in 2007. In other years, it fluctuated within a range of relative ecological security. Gabon had the best ecological security state in Central Africa, sustaining a high ecological security index with an average value of 0.81. Other countries had values that fluctuated greatly early in the study period but these tended to stabilize in later years.

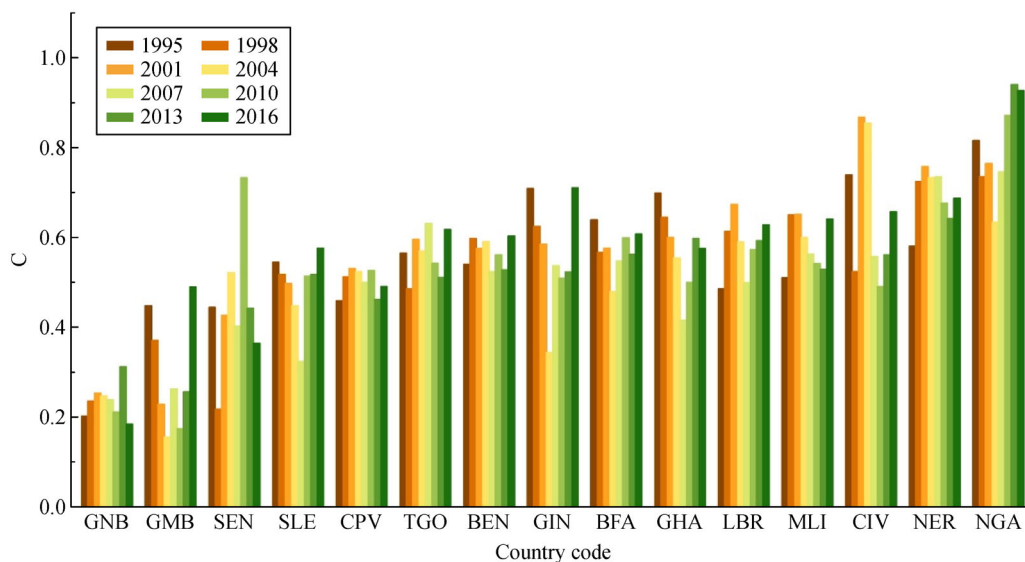


Fig. 3 Variations in ecological security index in West Africa. C is the ecological security index, and the value reflects the state of ecological security, 0.0 and 1.0 indicated the worst and the best, respectively. Country code is abbreviated country name. GNB, Guinea-Bissau; GMB, Gambia; SEN, Senegal; SLE, Sierra Leone; CPV, Cape Verde; TGO, Togo; BEN, Benin; GIN, Guinea; BFA, Burkina Faso; GHA, Ghana; LBR, Liberia; MLI, Mali; CIV, Cote d'Ivoire; NER, Niger; NGA, Nigeria.

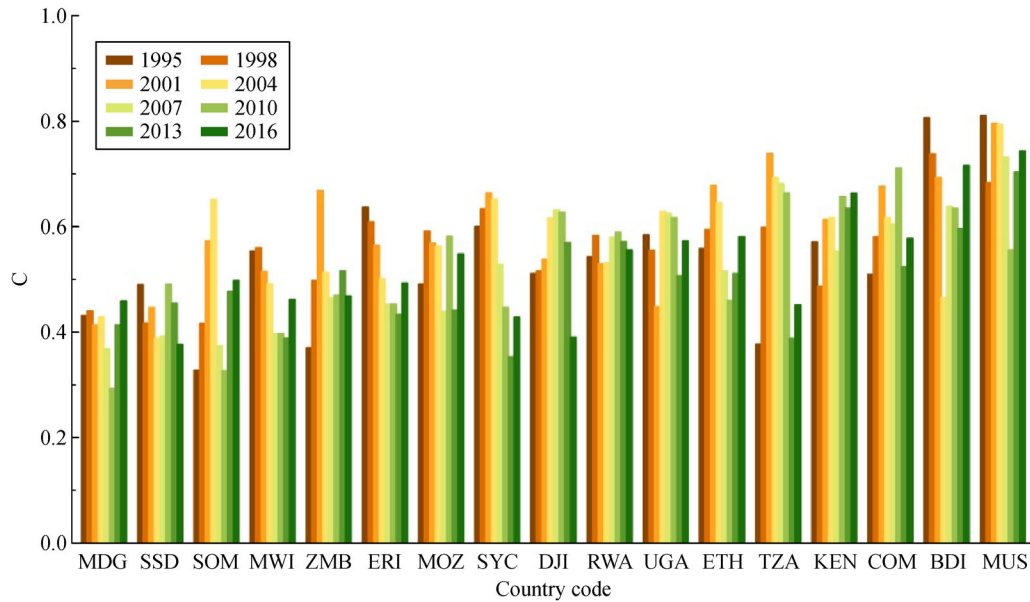


Fig. 4 Variations in ecological security index in East Africa. C is the ecological security index, and the value reflects the state of ecological security, 0.0 and 1.0 indicated the worst and the best, respectively. Country code is abbreviated country name. MDG, Madagascar; SSD, South Sudan; SOM, Somalia; MWI, Malawi; ZMB, Zambia; ERI, Eritrea; MOZ, Mozambique; SYC, Seychelles; DJI, Djibouti; RWA, Rwanda; UGA, Uganda; ETH, Ethiopia; TZA, Tanzania; KEN, Kenya; COM, Comoros; BDI, Burundi; MUS, Mauritius.

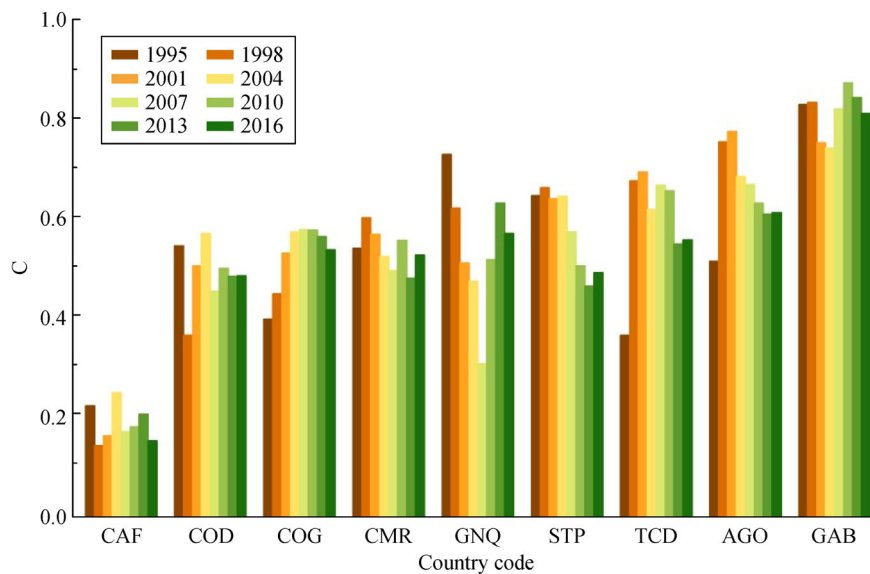


Fig. 5 Variations in ecological security index in Central Africa. C is the ecological security index, and the value reflects the state of ecological security, 0.0 and 1.0 indicated the worst and the best, respectively. Country code is abbreviated country name. CAF, Central African Republic; COD, Democratic Republic of the Congo; COG, Republic of the Congo; CMR, Cameroon; GNQ, Equatorial Guinea; STP, Sao Tome and Principe; TCD, Chad; AGO, Angola; GAB, Gabon.

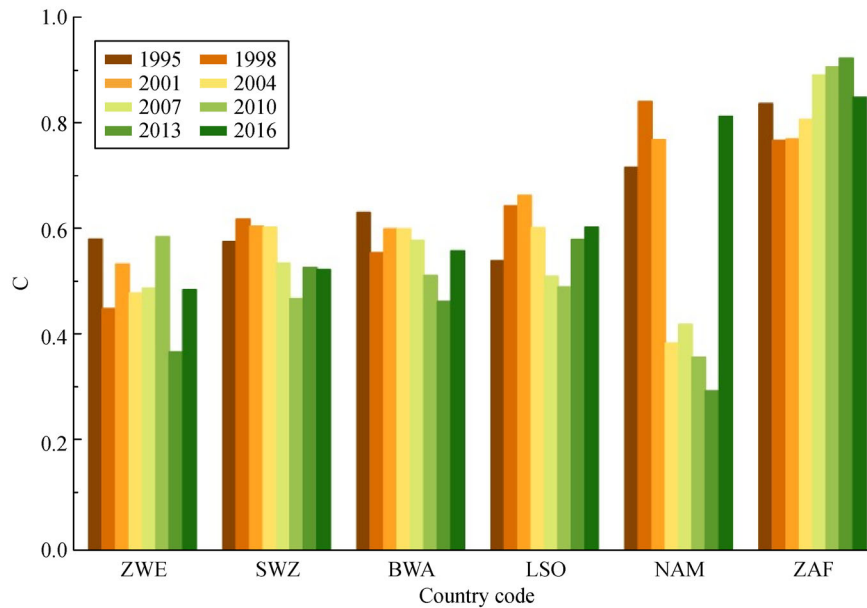


Fig. 6 Variations in ecological security index in Southern Africa. C is the ecological security index, and the value reflects the state of ecological security, 0.0 and 1.0 indicated the worst and the best, respectively. Country code is abbreviated country name. ZWE, Zimbabwe; SWZ, Swaziland; BWA, Botswana; LSO, Lesotho; NAM, Namibia; ZAF, South Africa.

3.1.5 Variations in the ecological security index in Southern Africa

Of the six countries in Southern Africa, the ecological security index in the Republic of South Africa was the highest (Fig. 6). In 1998 and 2016, however, the value decreased to 0.76 and 0.85, respectively. Despite these dips, the values tended to increase gradually. Ecological security remained within the range of 0.65–1.00. In contrast, the ecological security of Zimbabwe fluctuated throughout the period as did the index for Namibia had obvious fluctuations as well, which decreased sharply from 0.77 in 2001 to 0.38 in 2004. Its value remained low until 2013 but recovered to 0.81 in 2016. Other countries (Botswana, Lesotho and Swaziland) had values that remained basically stable, fluctuating within the range of 0.50–0.65, showing little change in ecological security.

3.1.6 Summary of variations in the ecological security index

We found that the ecological security index and its variation differed among the five regions during the study period. Countries whose index was above 0.65, such as Algeria, Egypt, Morocco, Nigeria, and the Republic of South Africa, were all relatively developed countries for Africa. They have a good economic base, rich natural resources, and a stable domestic political situation. Data from the International Monetary Fund showed that the GDP of Nigeria, the Republic South Africa and Egypt

in 2017 was 376.361 billion, 349.299 billion and 236.528 billion, respectively. These are the top three African countries, closely followed by Algeria, Morocco and Angola. Despite considerable annual variation in the ecological security index of these countries, the range of this variation was small.

The ecological security index for the Central African Republic, Gambia, Guinea-Bissau, and Libya was relatively low. Indeed, their domestic conditions are the opposite of those mentioned above. Their economic base is weak, and agriculture is their main economic activity. Also, their political situations do not provide cause for optimism, with civil war and various conflicts occurring frequently. Basic quality of life for a majority of people in these countries is difficult to guarantee. In a word, we evaluated the ecological security by the 26 economic, natural, and societal indicators of the evaluation system and our results showed that national development potential have a greater impact on ecological security than others.

3.2 Temporal-spatial variations in ecological security in Africa (1995–2016)

3.2.1 Temporal variation of ecological security level in Africa from 1995 to 2016

Based on data processing methods and the classification standard for ecological security, we obtained the temporal-spatial variation of the ecological security level in Africa from 1995 to 2016 (Fig. 7). The number of countries at

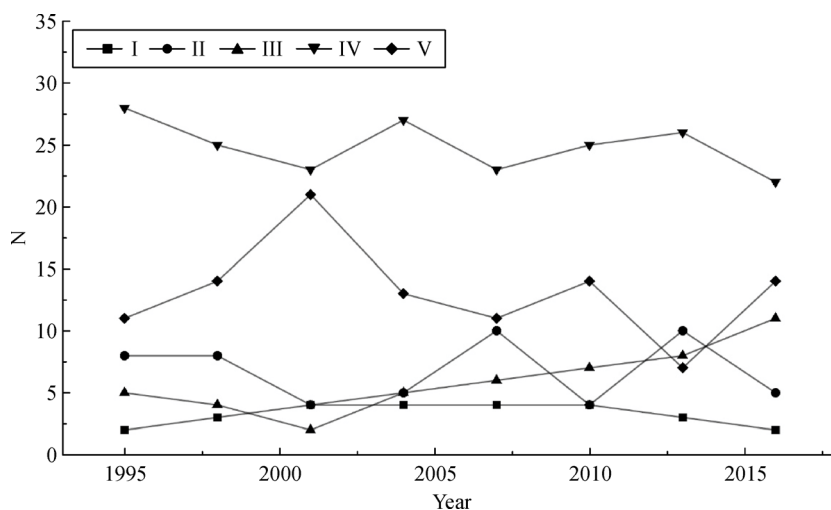


Fig. 7 Variation of ecological security level in Africa from 1995 to 2016. Ecological security levels I–V represent the ecological security state. I, extremely unsafe state; II, unsafe state; III, critical safe state; IV, relatively safe state; V, safe state. N is the number of countries in each level.

different levels varied significantly in the study period. Note that the ecological security index was typically above 0.50. Therefore, the ecological security of most African countries was at level IV or V (Table 1).

Unlike distinct changes in other levels, the number of countries at level I was quite stable at four from 2001 to 2010 (viz., Central African Republic, Gambia, Guinea-Bissau and Libya), with the addition of Madagascar in 2010.

About half of the countries were at level IV. In other words, most countries were relatively safe. Second in number were countries whose ecological security state was at level V. Although their annual variation was irregular and the trends for them (levels IV and V) were opposite to those of the countries at level IV, showing a decline, while the number at level IV increased, apart from 2004 to 2010. There were around 40 countries at either level IV or V and the number was generally constant. It was notable that when this number decreased, the number of countries at level II increased significantly. In 2007, for example, the number at level II was the highest (10), making this the worst year for ecological security during the study period. Parts of some countries underwent military coups successively in 2003, including the Central African Republic, Guinea-Bissau, Mauritania^[43]. Also, local factors in Africa were volatile from 2004 to 2007, with incidents of tribal and religious violence and deaths from various terrorist attacks. Violent crimes increasing markedly^[44] and these events affected the ecological security state in Africa. With persistent development, however, the economic and political situation improved significantly, and many countries became stable. In general, ecological security has been improving, and the number of countries at levels I and II has decreased.

3.2.2 Spatial variation of ecological security level in Africa from 1995 to 2016

Overall, the ecological security of most African countries was good, with only a few countries changing frequently such that their ecological security was unstable during the study period.

At the beginning of the study period, the ecological security of Africa was relatively safe in many countries, and it tended to improve over time. Overall, 2001 was the best year for ecological security in Africa, with the highest number of countries at level V and the lowest number of countries at levels I and II. Only a few countries had poor ecological security. For example, the Central African Republic and its surrounding area. Moreover, Libya, in North Africa, showed deteriorating ecological security from 1995 to 2007. Indeed, the Central African Republic is a country that is quite underdeveloped. In addition to a weak economy, political instability is the main reason for this. Frequent civil war and religious conflict render it a thoroughly unstable state. Peacekeeping forces and the international community have been necessary to mediate in these conflicts.

From 2004 to 2013, Central Africa underwent frequent changes, and its ecological security was threatened. Meanwhile, Madagascar, whose ecological security state remained unstable throughout the period, had extremely poor ecological security in 2010. The situation in Central Africa was partly affected by surrounding countries, which were seldom in a relatively safe state. From 2007 to 2016, countries close to the Central African Republic were at level III, that is, with threatened ecological security.

In recent years, the variation in ecological security in African countries has become more complex. It is not only

concentrated in Central Africa, but also scattered throughout other regions. Nevertheless, in 2016, the ecological security of Africa as a whole improved compared to that in 2013. There were fewer areas with poor ecological security, and some countries that were relatively safe before became even more so. This shows that the development of ecological security is closely related to the international environment and to the recovery of African economies.

3.2.3 Comparison of the level of ecological security in the five regions

The ecological security index for the five regions in Africa from 1995 to 2016 is shown in Table 2. The ecological security in these regions can thus be compared. Based on the mean ecological security index from 1995 to 2016, all five regions had relatively safe state.

North Africa, which includes seven countries, had the highest ecological security index (0.61) among the regions. Except for the situation in Libya, which has a difficult political and security situation, other countries were relatively safe. For example, Egypt and Algeria remained at level V throughout the period and in general, North Africa had the best ecological security in the continent. According to the definition of ecological security, and taking into account the specific region of North Africa, its natural, economic, and social status was relatively good compared to other regions. Due to its geographical location, it benefitted from several advantages, including exports and tourism^[45]. Moreover, the climate in North Africa is mainly Mediterranean and tropical desert. A Mediterranean climate, with hot, dry summers, and cool, variably rainy winters, facilitates local agriculture and is comfortable for people to live. A tropical desert climate means that the population is less dense. Further, the fertility rate in North Africa is less than in other regions. Therefore, per capita resources are relatively higher. Previous studies have also shown that urbanization in North Africa is higher. Algeria and Morocco in particular have urbanization rates above 60%, and the overall level of urbanization in North Africa is high^[46,47]. Thus, many factors positively

impact ecological security in North Africa.

Southern Africa is the second highest of the five regions. Besides, the others are almost the same in ecological security index. From the perspective of national security level, however, there are 3 countries, Gambia and Guinea-Bissau in level I and Senegal in level II, which are below critical safe state (level III), and they account for 20% of total West Africa countries. As a result, West Africa has the worst ecological security state among the five regions. Although Nigeria reached level V, unbalanced development in the region lowered the ecological security state. Although West Africa is one of the poorest regions in the world, according to the International Monetary Fund's report, *Regional Economic Outlook—Sub-Saharan Africa*^[48], economic development prospects for West African countries are optimistic. In addition, the region has experienced its highest level of development over the past 20 years. Consequently, the ecological security in Africa as a whole and West Africa in particular is likely to improve.

4 Conclusions

At the national level, the ecological security of the 54 countries in Africa varied considerably, as did spatial and temporal variations from 1995 to 2016. The ecological security of most African countries was at level IV or V. The years 2007 and 2001 were the worst and best years for ecological security during the study period, respectively.

At the regional level, the ecological security of North Africa was greater than other regions in Africa. In contrast, because the ecological security of Gambia, Guinea-Bissau and Senegal were below level III, unbalanced development in the region lowered the ecological security state. So West Africa has the worst ecological security state in the five regions.

Our results showed that national development potential have a greater impact on ecological security than others. Based on the broad definition of ecological security and the basic principles of the PSR model, we evaluated the ecological security state of Africa, and our results cannot

Table 2 Level compare of ecological security in the regional

| Region | Mean | Max | Min | The number of countries at different levels | | | | | Total number (I–V) |
|--------------------|------|------|------|---|----|-----|----|----|--------------------|
| | | | | I | II | III | IV | V | |
| North Africa | 0.61 | 0.75 | 0.33 | 0 | 1 | 0 | 3 | 3 | 7 |
| West Africa | 0.54 | 0.80 | 0.23 | 2 | 1 | 1 | 8 | 3 | 15 |
| East Africa | 0.54 | 0.72 | 0.40 | 0 | 2 | 3 | 10 | 2 | 17 |
| Central Africa | 0.54 | 0.81 | 0.18 | 1 | 0 | 1 | 5 | 2 | 9 |
| Southern Africa | 0.60 | 0.84 | 0.50 | 0 | 0 | 0 | 5 | 1 | 6 |
| Total number (I–V) | | | | 3 | 4 | 5 | 31 | 11 | 54 |

Note: Ecological security levels I–V represent the ecological security state. I, extremely unsafe state; II, unsafe state; III, critical safe state; IV, relatively safe state; and V, safe state.

only provide guidance and ideas for the study of ecological security of large scale region, but also, following the trend of current world, supply data support for scientific development of African countries.

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Compliance with ethics guidelines Huihui Wei, Wenjuan Zhang, Feng Zhang, and Guojun Sun declare that they have no conflicts of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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