International Journal of Sciences: Basic and Applied Research (IJSBAR)

ISSN 2307-4531
(Print & Online)

http://gssrr.org/index.php?journal=JournalOfBasicAndApplied

Remote Sensing and GIS Analysis of Deforestation and Desertification in Central Highland and Eastern Region of Eritrea (1972-2014)

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Abstract

The integration of remote sensing technology (RST) and geographical information system (GIS) are suitable to extract the dynamic change of forest and desert land cover in arid and semi-arid regions. In this study, we used Landsat data to quantify forest and desert cover change in central highland and eastern region of Eritrea (1972-2014). Each satellite image was classified into three land cover categories, and post-classification was implemented to analyze and interpret change detections. The study demonstrated that the average value of the overall accuracy and the kappa statistics was 98.45% and 97.40%, respectively, and about 8.38% and 28.21% of the study area was covered by forest and desert, respectively, in 1972 and 2014. In 2014, about 2.42% of the total forest and about 4.04% of the total arable land cover was lost, respectively, due to deforestation and desertification. The highest annual rate of deforestation ($15.23km^2y^{-1}$) and desertification ($44.38km^2y^{-1}$) were recorded between 1972 and 1985, however, the trend of annual rate of deforestation and desertification was gradually decreasing. Therefore, deforestation and desertification were serious problems in Eritrea, and climate change such as rainfall variability and drought, and human activities are might be the main factors.

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Keywords: deforestation and desertification; Eritrea; Landsat data; supervised classification

1. Introduction

Environmental degradations such as desertification and deforestation are the major environmental problems in the world. Desertification is the process of environmental degradation, which commonly occurs in arid, semi-arid and dry sub humid regions of the world [12, 20, 41] including Eritrea. It covers more than 30% of the earth's land surface [28], in other words it happens where evapotranspiration is much higher than precipitation [11]. Deforestation is also a concern of the entire globe, especially in less developed countries like the Sahel and east African countries. Forest ecosystem covers about 40% of the world, which provides inevitable resources including timber production to the world population [26], despite these vital benefits, the forest ecosystem is continuously under pressure from anthropogenic activities, especially tropical forests [13].

Desertification and deforestation are serious environmental concerns in the Sahel and East African countries including Eritrea, and climate change such as drought and human factors are primary reasons [31]. The Sahel region is characterized with scarcity of rainfall [2] as a result drought becomes the major environmental problem where the rate of desertification and deforestation reaches at the highest stage. There are several drought reports in the Sahel region from 1960s to 1980s. The disastrous drought in 1960's and 1970's [16], a lasting drought from 1960s and 1980s leads water deficit of 25 to 40% [21] and the drought between 1972–1973 and 1983–1984 [2] are some examples of catastrophic droughts in this region. [37] 1991, had explained the catastrophic effect of droughts and famine in Ethiopia and Eritrea from 1970s to 1980s, in his book '*Thirty Years of War and Famine in Ethiopia' EVIL DAYS*. The anthropogenic impact and rural population pressure over land leads to a major concern in Africa, particularly, in east Africa as transforming of natural environment predominantly through pastoralism, shifting cultivation, semi-permanent agriculture [3]. This is true to Eritrea and Ethiopia were respectively, more than 80% [24] 2012, 83% [31] of their population depend on primary economic activities; consequently, burden to land is extremely high. Although, there are limitations in reliable historic data on forest cover and the extent of deforestation rates in Eritrea, around 1900, 30% to 40% of the land surface was covered by forest [25], currently, 13.7% the total land area remains under forest cover including woodland forests [23,1].

The birth of RST in 1970s [3] is vital to the world, which plays a very big role in monitoring of land degradations and analysis of land use changes. However, the application of this technology is limited in less developed countries such as Eritrea while it is a valuable tool to evaluate environmental changes in the Sahel region [4], this is mainly due to lack of access and poor education. In Eritrea, the use of RST and GIS applications for monitoring and handling of the environment is very limited particularly, in desertification and deforestation. Different scientific approaches including remotely sensed satellite images and GIS are evolved for analysis of land cover change over a range of periods [38, 17]. Landsat data also uses to investigate land degradation such as desertification and deforestation prone areas and RST and GIS investigation of environmental degradation is more effective than field surveys in terms of cost, time and area coverage [7].

Our study in the central highland and eastern region of Eritrea aimed to quantify the change of forest and desert coverage over the period of 1972 to 2014 with the application of remote sensing and geographical information system. In addition, this study aimed to contribute a better understanding about desertification and deforestation processes in Eritrea and to supply an input data for further studies.

2. The Study Area

Eritrea is located in the Horn of Africa, and the study area stretches from central highland toward the coast in the eastern lowland, where arid and semi-arid regions are dominant. It is located in the geographical coordinates of 15^{o}13'12", 14^{o}59'9", 16^{o}48'33" and 16^{o}43'43" North and 38^{o}17'17", 39^{o}57'4", 38^{o}37'59" and 38^{o}7'55" East, generally, it covers about 19,232 km^2, which is 1/6th area of the country (fig. 1). The study area is situated in socio-economic sphere of three big cities; Asmara, the capital city in the central highland, Massawa in the eastern part of the study area, which is the port and capital city of Northern Red Sea Zone and Keren in the western side of the study area, is the capital city of Anseba region. Majority of the people in this region depend on farming and livestock such as cattle, goats, sheep and camels. The region characterized with uneven population density where the central highland is the most densely populated region while the eastern region of the study area is sparsely populated. Like other east African countries, majority of the people in the rural area depend on firewood for cooking and as a source of income by selling dry wood or charcoal in the above big cities, whereas the urban people highly depend on charcoal [14].

The study area comprises a very complex topography, which includes bisected highlands, hills, escarpments, coastal area and it has several rivers and many small tributaries that drain eastward to the Red Sea. The overall elevation ranges from sea level in the coast to about 2500 meter in the central highland [33]. The study area has arid, semi-arid and sub-humid climate, which is located along the Sahel region, is a transition zone between the Saharan desert and Sub-Saharan countries. However, the geographical setups of the region play a great role in regulation of rainfall and temperature. In addition, the prevailing winds from Atlantic and Indian oceans in summer season (rainy season) and central Asia in winter season (dry season) provides rainfall to the coastal and eastern escarpments. Generally, the climate of the region gradually changes from extremely hot and dry climate at the coast to warm and wet climate at the top of the eastern escarpment and central highland [18, 8]. The annual average rainfall in the study area varies from less than 200 mm in the coastal region to around 1000 mm in the eastern escarpment, which receives rainfall twice a year and about 600 mm in the central highland. High correlation exists between mean annual temperature of the study area and altitude, which the mean annual temperature ranges from about 30^{o}C at sea level to 16^{o}C around Asmara, 2500 m [24]. Shrubs are the most dominant vegetation in the study area and forest cover found in the eastern escarpment whereas desert covers predominantly from the coastal region toward inland about 600 km. Therefore, the region is suitable to study both deforestation and desertification at the same time.

3. Data and Method

3.1 Landsat Data

Cloud free Landsat images were selected for our study from the United States Geological Survey (USGS) based on the accessibility of free downloadable images; four (geo-tiff) Landsat data (MSS, TM, ETM+ and OLI_TIRS) were downloaded from 1972, 1985, 2000 and 2014, respectively. A satellite image with scene number of 169 and 49 for path and row was needed from 1985, 2000 and 2014. However, three Landsat images were downloaded from 1972 (table 1). RST (ENVI 4.7) and GIS (ArcGIS 9.3) were the main tools for image processing in building computations and mapping. See table 1 for detail information. The digital elevation model (DEM) for our study was obtained from (SRTM) the Shuttle Radar Topography Mission.

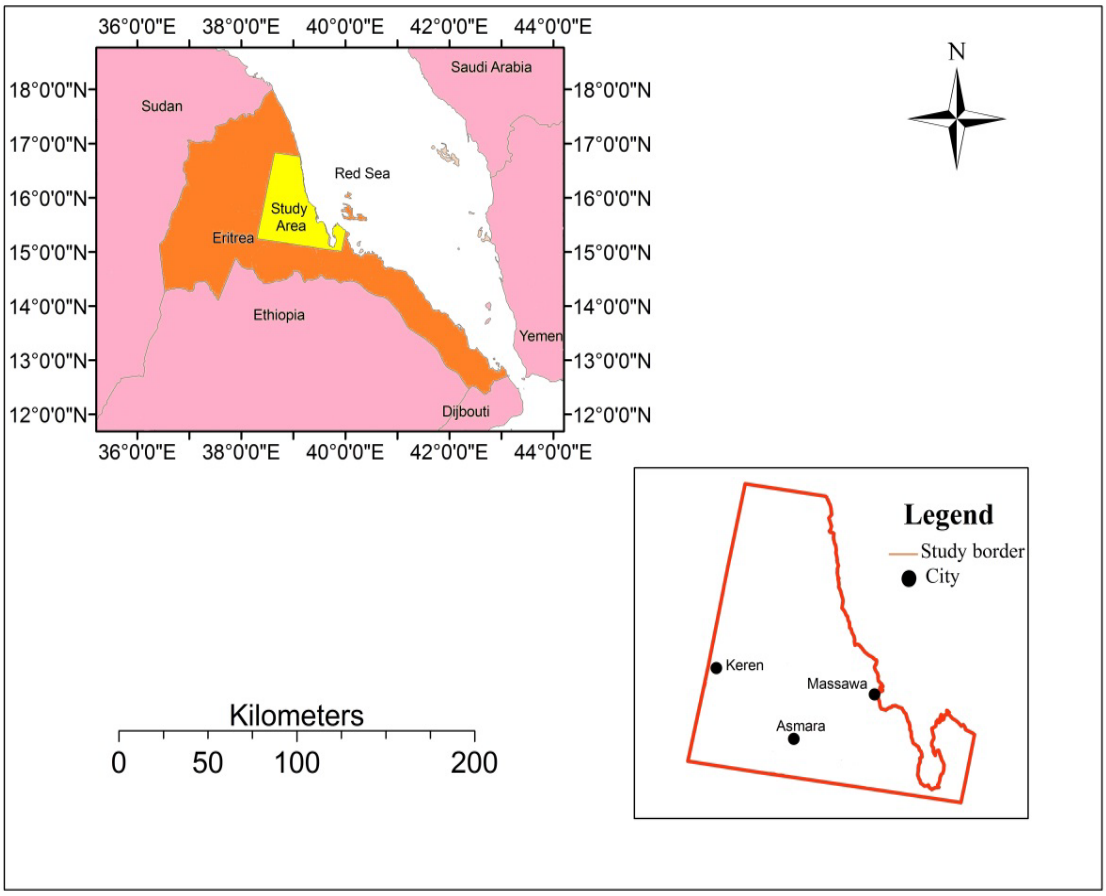

Figure 1: shows the location of the Country, the study site (A) and major cities in the study area (B).

3.2 Digital Image processing

The pre-processing of Landsat image and digital elevation model (DEM) for our study were executed using ENVI 4.7. Three bands with (green, red and near infrared) were imported to ENVI 4.7 for each Landsat image, and we applied layer stacking to convert into a layer file. The Landsat images were geo-referenced and projected to WGS84 datum on Universal Transverse Mercator Projection (UTM) zone 37 N using a designed python program and geometrically corrected [5, 6, 34]. The satellite images were calibrated and manipulated [7], and atmospheric correction was carried out using IAR Reflectance module. The images from 1972 were mosaicked into a single image file and converted the spatial resolution from 57 m to 30 m in order to have the same resolution with the Landsat images from 1985, 2000 and 2014. We used a vector shape file to cut each image into a desired size using building a mask. DEM data with 30 m resolution was also pre-processed in ENVI 4.7 software to identify the different physiographic units of the study area. We used the same vector shape file to cut the DEM image to the size of the study area.

Table 1: the summary of Landsat data and the NDVI bands

Date	Landsat Sensor	Spatial Resolution (m)before converted	Spatial Resolution (m)after converted	Lat/Long	Path/Row	NDVI bands
12/2/1972	MSS	57	30	17.3/39.0	182/48	2 & 3
				15.9/38.7	182/49	
				15.9/40.1	181/49	
14/3/1985	TM	30	30	15.9/39.3	169/49	3 & 4
27/1/2000	ETM+	30	30	15.9/39.3	169/49	3 & 4
01/5/2014	OLI_TIRS	30	30	15.9/39.3	169/49	4 & 5

3.3 Image Classification Processing

In our study, we adopted supervised method of classification with maximum likelihood naturally, nearby neighbor algorithm, because the accuracy of the supervised classification sounds to be more suitable than the unsupervised method [38, 15]. Training site for this study was generated from field survey, and NDVI (Normalized Difference Vegetation Index). Although the classification depends on supervised method, the NDVI value helped us to have a general knowledge about the distribution of vegetation in the study area, particularly forest (as the highest NDVI value) and desert (as the lowest NDVI but very close to zero, since negative NDVI value refers to water in our study) (fig. 2). Vegetation index is calculated from visible (red) and near infrared (NIR) bands, which is NDVI=NIR – red/NIR + red [2, 6, 17, 40, 41].

3.4 Error Matrix

Confusion matrix (error matrix) was performed using ground truth ROIs (region of interests) to evaluate and assess the classification accuracy, which the matrix computes the accuracy of each class directly [19]. Thus, the statistical value of overall accuracy, kappa coefficient, omission error (producer's accuracy) and Commission error (user's accuracy) for 1972, 1985, 2000 and 2014 was computed in ENVI 4.7 automatically after each classification has been completed, and the process repeated until the result becomes satisfactory. The kappa statistics showed that the probability of an agreement that could be expected to present by chance [39], and the value ranges from +1.0 to -1.0, on the other hand, it ranges, respectively, from strong agreement to poor agreement [36].

3.5 Image Post-processing

The Landsat images and the DEM were exported from ENVI 4.7 software to ArcGIS 9.3 for farther analysis. The area and percentage of the forest and the desert cover change for each epoch computed from the pixels. The confusion matrices were also exported to a table function (Excel) for farther analysis and interpretation, where the statistical value of overall accuracy, kappa coefficient, and omission and commission errors calculated to evaluate the classification accuracy [10]. The annual rate of deforestation and desertification in each epoch between 1972-1985, 1985-2000, 2000-2014 and 1972-2014 was analyzed and interpreted, and the annual rate of deforestation expressed either in rate (area/time) or in percentage [35]. In this study, the following formula was applied to compute annual rate of deforestation as well as annual rate of desertification [29, 31].

$$R = \frac{A_1 - A_2}{t_2 - t_1} \quad \text{or} \quad R = \frac{A_1 - A_2}{A_1} * 100$$

Where R, is the annual rate of deforestation, A_1 & A_2 refer to area of forest cover at time t_1 and t_2, respectively.

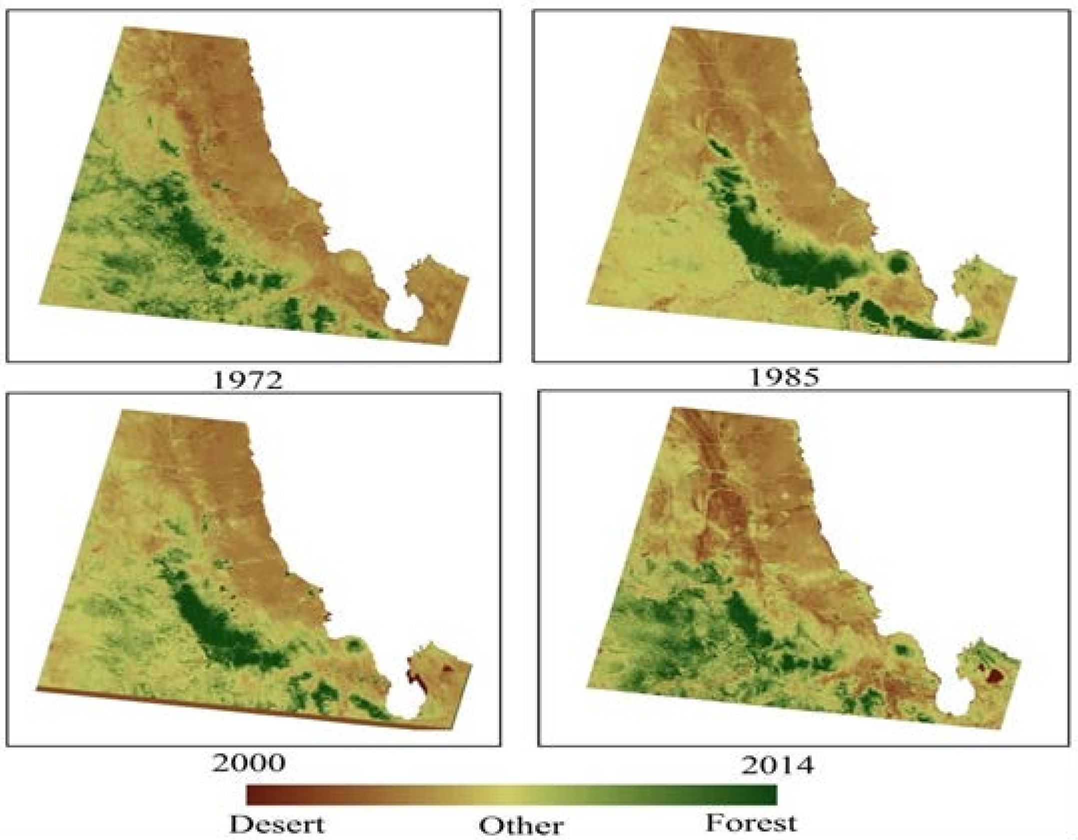

Figure 2: shows the NDVI map of the Study area from 1972, 1985, 2000 and 2014, and the color symbols stated that the deep green at the center of the map to forest, the brown near the coast to desert and the light brown which is dominant in the central highland to other land cover.

4. Result

4.1 Landsat Classification Assessments

Figure 3 explains the land cover of forest, desert and other from 1972, 1985, 2000 and 2014, and it reveals that desert is dominant land cover in eastern, northeast and southeast, and northwest and southwest of the study region along the coast whereas forest is predominantly located in the eastern escarpment of the region. Desertification was extremely high at the margins of desert area particularly, in northwest and southwest part of the study area and central highland, whereas deforestation was common everywhere in the study area mainly, in the central highland and eastern escarpment where the forest cover is dominant. According to the results (table 2), in 1972, about 1610 km^2 and 5425 km^2 of the total land cover of the study area was classified as forest and desert respectively, this covers about 36.58% of the total region. In 1985, forest cover declined by 1.40%, while the desert area expanded to 6002 km^2, which is about 3% of fertile land was converted into unproductive land within 13 years (1972-1985). In 2000, the forest cover declined to 1235 km^2 and the desert area increased to around 6111 km^2. In 2014, around 463 km^2 of forest area was lost in the last four decades, and the desert cover was increased to 6198 km^2, which is about 773 km^2 of arable land was lost from 1972 to 2014.

Table 2: explains the summary of each land cover change in area (km^2) and percentage from 1972 to 2014

Class	1972		1985		2000		2014	
	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)
Forest	1610	8.38	1412	7.34	1235	6.43	1147	5.96
Desert	5425	28.21	6002	31.2	6111	31.8	6198	32.2
Other	12195	63.41	11818	61.5	11870	61.7	11886	61.8

4.2 Classification Accuracy Assessment

In our study, forest and desert land covers were extracted with high kappa coefficient and overall accuracy. Table 3 explains the confusion matrix and table 4 shows commission, omission, user and producer accuracy in percentage for 1972, 1985, 2000 and 2014. In 1972 and 2000, 100% of the desert cover extracted with 0% omission error. 99.36% and 99.14% with user accuracy of 99.79 and 98.98% of the forest cover extracted, respectively, in the same year. In 1985 and 2014, the classification accuracy was also high, about 97.75 and 96.52% of the forest cover was classified with 99.67 and 92.42% of user accuracy. In the same year, 99.87 and 96.37% of the desert cover performed with omission error of 0.13 and 3.63%, respectively.

Table 5 also explains the overall accuracy and the kappa coefficient of classification from 1972 to 2014, the general value of the overall accuracy and the kappa coefficient were averaged to 98.45% and 97.40%, respectively. According to the explanation and interpretation of kappa statistics, our value ranges within strong agreement**.**

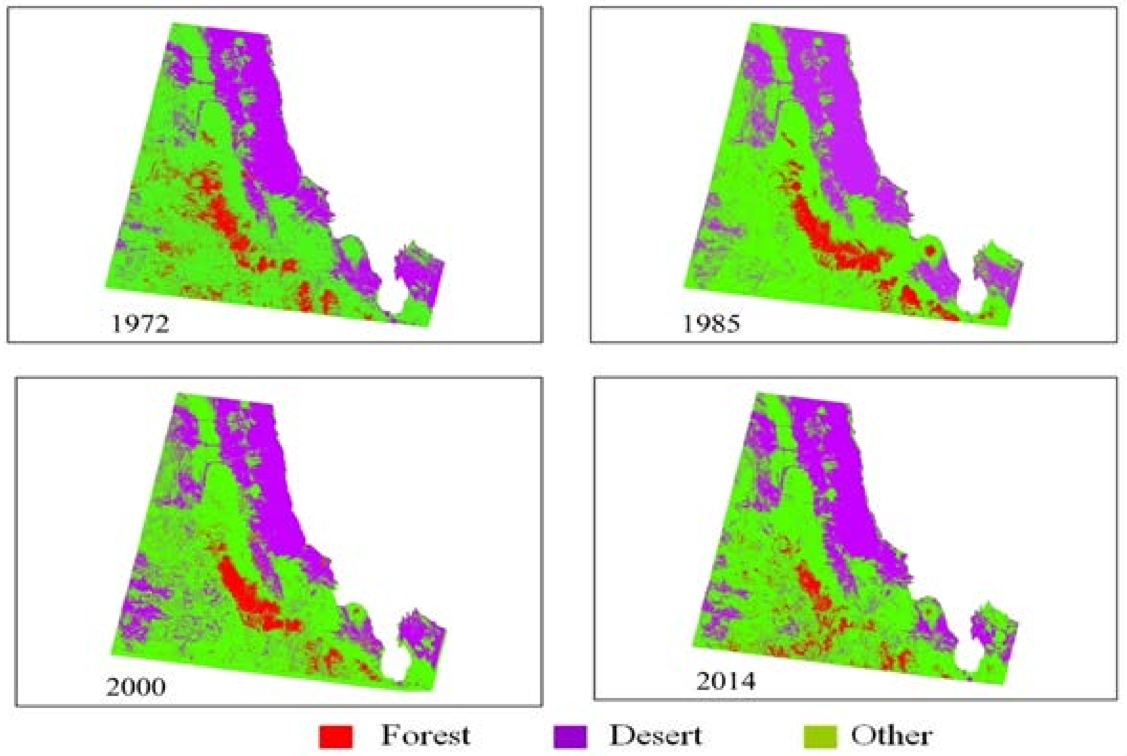

Figure 3: supervised classification of Landsat images of Forest, Desert and other land covers in the central highland and eastern region of Eritrea from 1972 to 2014.

Table 3: confusion matrices of land cover change based on ground truth ROIs (percentage) from 1972 to 2014.

Class	Forest	Desert	Other
		1972	
Forest	99.36	0	0.18
Desert	0	100	0
Other	0.64	0	99.82
		1985	
Forest	97.75	0	0.18
Desert	0	99.87	0.1
Other	2.25	0.13	99.71
		2000	
Forest	99.14	0	0.89
Desert	0	100	0
Other	0.86	0	99.11
		2014	
Forest	96.52	0	1.95
Desert	0	96.37	4.68
Other	3.48	3.63	93.36

4.3 Classification Change Detection

In this study, forest and desert land cover change has been detected where the forest cover has been reduced drastically due to deforestation and huge area of arable land was converted into infertile land due to desertification in the last 42 years. In 1972, some forest area sparsely distributed in the central highland while a very thick forest found in eastern escarpment of the region, and the desert area virtually stretched from the coastal area of the region toward the mainland. However, by the epoch of 1985 deforestation was serious especially, in the central region.

Table 6 explains about 198 km^2 of the total forest was lost from 1972 to 1985 and virtually all the forests in the central region were disappeared. Desertification was also significant, as the desert cover intensely expanded by 577 km^2 between 1972 and 1985. The image for 2000, demonstrated that deforestation and desertification were extremely high, generally, about 177 km^2 of forest cover was lost, and around 109 km^2 of arable land was lost between 1985 and 2000. The image for 2014 illustrated that the desert area expanded by 0.47% from 2000 to 2014, in the past four decades about 2.42% of forest area lost and around 4.02% of arable land was lost, respectively, due to deforestation and desertification. However, the rate of desertification was very low in 2014 comparing to the previous epochs, which displayed that forest cover regenerated in the central highlands even though deforestation was seemed unceasing process in the region.

Table 4: shows the commission, omission, user and producer accuracy (percentage).

Class	**Commission (%)**	**Omission (%)**	**User accuracy (%)**	**Producer accuracy (%)**
		1972		
Forest	0.21	0.64	99.79	99.36
Desert	0	0	100	100
Other	0.55	0.18	99.45	99.82
		1985		
Forest	0.33	2.25	99.67	97.75
Desert	0.06	0.13	99.94	99.87
Other	1.52	0.29	98.48	99.71
		2000		
Forest	1.02	0.86	98.98	99.14
Desert	0	0	100	100
Other	0.75	0.89	99.25	99.11
		2014		
Forest	7.58	3.48	92.42	96.52
Desert	4.06	3.63	95.94	96.37
Other	5.11	6.64	94.89	93.36

Table 5: shows overall accuracy and kappa coefficient from 1972 to 2014.

Year	Overall Accuracy	Kappa Value
1972	99.79%	99.67%
1985	99.47%	99.11%
2000	99.40%	99.10%
2014	95.13%	91.70%

Table 6: displays total area change in square kilometer and percentages from 1972 to 2014 Note: Negative number represents decrease in area (deforestation) and positive number represents increase in size (desertification).

Land cover	1972-1985		1985-2000		2000-2014		1972-2014	
	Total Area Change (Km^2)	Area Change (%)	Total Area Change (Km^2)	Area Change (%)	Total Area Change (Km^2)	Area Change (%)	Total Area Change (Km^2)	Area Change (%)
forest	-198	-1.04	-177	-0.91	-88	-0.47	-463	-2.42
desert	577	3.00	109	0.59	87	0.43	773	4.02
Others	-377	-1.96	52	0.32	16	0.04	-309	-1.6

Figure 4 explains the annual rate of deforestation and desertification between 1972-1985, 1985-2000, and 2000-2014. The highest annual rate of deforestation (15.23 km^2y^{-1}) and desertification (44.38 km^2y^{-1}) recorded between 1972 and 1985; however, the annual rate for both declined from 1985 to 2014. The rate of deforestation and desertification was decreased, respectively, to 11.8 and 7.27 km^2y^{-1} between 1985 and 2000 and it was dropped again to 6.29 and 6.21 km^2y^{-1}, respectively, between 2000 and 2014. Annually, about 0.68% forest was lost and 0.34% of the total area was changed into barren land from 1972 to 2014 due to desertification. However, the trend of deforestation and desertification was gradually decreasing from 1985 to 2014.

5. Discussion

Generally, remote sensing images and GIS are valuable tools to measuring, processing and monitoring of environmental degradation particularly, for desertification and deforestation in the Sahel regions [4] including Eritrea. Since study in this area is limited, to compare our result with others are difficult; however, the overall results revealed that the forest cover of the study area was gradually decreased whereas the desert area was steadily increased from 1972 to 2014. The annual rate of deforestation in the last four decades was 2.45 times higher than the entire annual rate of deforestation in the country (0.28%), estimating by [9], 2010. In 1985, deforestation was very high in the central highlands, this was perhaps due to human factors such as cutting trees for commercial and subsistence agriculture, firewood and timber, mismanagement of land, overgrazing, population and urban growth, and construction of houses (Hidmo) [1]. The typical traditional Eritrean highland home (Hidmo) takes about100 pillars or poles for construction, which means cutting of 100 live trees for a single house, etc. [23]. Another factor for deforestation was the war between Eritrea and Ethiopia, because the troops cut trees for construction of shelters, trenches and firewood [37]. Climate change such as inadequate and inconsistent rainfall, high temperature and drought are the main factors of deforestation.

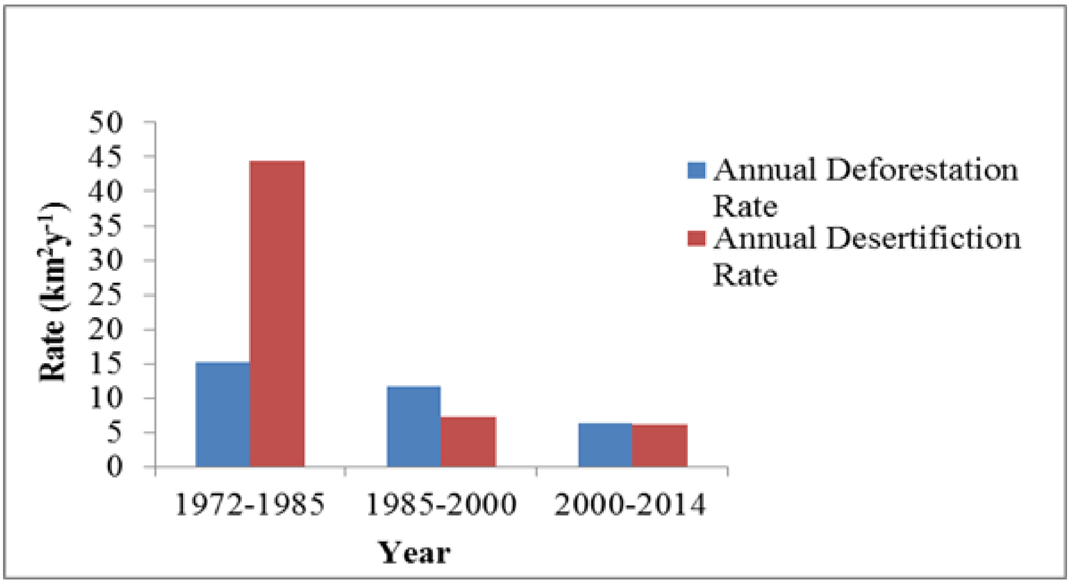

Figure 4: explains the change of annual rate of deforestation and desertification in (km^2y^{-1}) between 1972 and 1985, 1985 and 2000, and 2000 and 2014.

Desertification was another serious environmental problem in the study area as well as in the country, particularly, along the marginal area of the desert. The rate of desertification was extremely high from 1972 to 1985, where about 577 km^2 of productive land was changed into infertile land and the dry land along the margin of the desert were vulnerable to desertification. In addition, the human factors, which mentioned in the above paragraph, climate change such as inadequate amount, infrequent and erratic distribution of rainfall, high temperature, and frequent and prolonged drought intensified desertification. According to Ministry of Agriculture [23], 2002 in Eritrea, 12 droughts recorded from 1970 to 1989, among these, the droughts between 1972 and 1973, and 1983 and 1985 were the most disastrous, and there were 43% of water scarcity in the Sahel region including Eritrea within 20 years. The causes of desertification between 1985 and 2014 could be the same to climate change and human factors because there was a severe drought in Eritrea from 1989 to 1991. The border conflict between Eritrea and Ethiopia for three successive years from 1998 to 2000 also another factor for desertification as well as deforestation. The marginal economic activity of the rural people in selling of live trees in the market during drought periods was severely damaged the forests and intensified desertification [37]. Particularly, during the drought periods from 1989 to 1991 the rural people in the central highland were totally engaged in selling live trees for firewood in Asmara the capital city of the country.

In 2014, forest restoring observed in the central highlands, this is might be due to forest conservation policy through afforestation, reforestation and soil conservation programs, which was started by the government after independence. Besides, no prolonged and severe droughts occurred in Eritrea between 2000 and 2014 except between 2000 and 2004 in the horn of Africa [18]. Commonly, deforestation was serious environmental problem in the central highlands, which frequently occurred at the top, bottom, along rivers and roads of the eastern escarpment of the region. However, the trend of the annual rate of deforestation and desertification from 2000 to 2014 was decreasing because of the above programs, which were conducted by student summer work, community, Warsay Ykalo campaign [23, 18].

6. Conclusion

The application of RST and GIS is suitable to produce an accurate forest and desert change detection and statistics in central highland and eastern region of Eritrea within the last four decades from 1972 to 2014. The result revealed that the integrated work of RST and GIS is suitable for classifications of land cover dynamics in any Landsat image (such as MSS, TM, ETM+ and OLI_TIRS) and analysis of patterns and trends of land cover change, particularly for forest and desert land cover changes. This technology is more reliable, certain and save considerable time, cost and efforts comparing to traditional method. Generally, the statistical findings of this study demonstrated that the forest and arable land coverage lost throughout the period. Human and climate change were probably the main factors of deforestation and desertification in this region. Action measure is essential for monitoring and management of deforestation and desertification. Thus, this study may use as input data for land management and policy decision makers. It may provide an opportunity for environmental management and monitoring of deforestation and desertification and it may be useful for further investigation at local, national or global scales for the unceasing shrinkage of forest and fertile land cover in Eritrea.

Acknowledgement

The National Science Foundation of China (grant No. 41271024) supports this work. We thankful Zeng Biao, Hongzhen Tian, Goush Fissehatsion and others who provided their efforts and comments to improve the organization, clarity and quality of the manuscript from the Institute of Glaciology and Eco-geography, College of Earth and Environmental Sciences, Lanzhou University and others.

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