AN ABSTRACT OF THE THESIS OF

Biniam Iyob for the degree of Master of Science in Geography presented on November 11th 2005
Title: Mapping Vegetation Using Landsat TM and ETM+ in Eritrea

Abstract approved:

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Julia A. Jones

The objective of this study was to examine vegetation and vegetation change in Eritrea over a period from the mid 1980s to 2002 using satellite remote sensing, and relate observed changes to the recent history of drought and war in the region. Specific objectives were (1) to examine vegetation change in Eritrea (NE Africa) from the mid 1980s (1984, 1985 and 1986) to 1999, 2000 and 2002; (2) to map vegetation into three vegetation categories: desert, highland shrubs, and forest and (3) to analyze whether vegetation classes and/or changes differed among three vegetation remote sensing indices. Eritrea has an area of 2,234 km^2 and occupies 1151 km along the Red Sea coast, with elevations ranging from -75m below sea level to 3018m. The climate is primarily arid to semi-arid, and vegetation is predominantly semi-arid and woodland. Population is sparse in the coast but dense in the central highlands. Eritrea experienced drought in the mid 1980s and again from 2000 to 2004. It also experienced two periods of war, from 1961 to 1991 and from 1998 to 2000. Vegetation was expected to increase during the 1990s in the absence of war and drought, but to decrease during periods of war and drought in the mid 1980s

and 1999-2002. The study was conducted using eight pairs of Landsat TM and ETM+ images over eight study areas spanning the range of topography, climate, and population density in Eritrea. Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and the Tasseled Cap Greenness (TC Greenness) indices were used to detect vegetation. The factors used to explain vegetation change were Moisture Stress Index (MSI), Tasseled Cap Wetness (TC Wetness), annual rainfall amount, topography, drought, rivers, deforestation, and land use. Analysis of Variance (ANOVA) was used to test for differences among the three vegetation indices. The classification confirmed the presence of deserts in the coastal areas, highland shrubs in the central highlands and forests in Southwest Eritrea, the Southern Highlands, and in some portions of Eastern Eritrea. However, vegetation change in Eritrea over the study period varied according to location and time period. NDVI, SAVI, and TC Greenness values were generally higher in Southern Highlands, South Western Lowlands and Western Escarpment during 1999 than in 1984 and 1986; this finding was consistent with the expectation that vegetation had recovered after the war and drought of the late 1980s. However, vegetation decreased in the 2000 to 2004 period in the Coastal plains, North East Sahel and West Sahel mainly due to drought. There was no significant difference among NDVI, SAVI, and the TC Greenness index when the assessment was conducted at large scale, while one small scale study area showed a difference between NDVI and TC

Greenness. Tasseled Greenness Cap seemed to be the most reliable of the three indices as it has a more reliable soil correction factor. Satellite image analysis using vegetation indices provided useful indicators of vegetation change that could be related to climate and war in Eritrea.

Mapping Vegetation Using Landsat TM and ETM+ in Eritrea

by
Biniam Iyob

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Biniam Iyob, Author

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Mapping Vegetation Using Landsat TM and ETM+ in Eritrea

1 INTRODUCTION

Eritrea is a country located in the Horn of Africa, north of Ethiopia, bordering the Red Sea. It was founded as a colony by Italy in 1890 and remained so until 1941. In 1941 (during the Second World War) the British army drove the Italians out and occupied Eritrea until 1951. In 1951, Eritrea was federated with Ethiopia for 10 years. Eventually, Emperor Haileselassie of Ethiopia annexed Eritrea in 1961, at which point Eritreans started an armed struggle for independence. Eritrea became independent in 1991. In 1993 a referendum was conducted and more than 99% of the population chose to be independent from Ethiopia, leading to the official recognition of Eritrea as a sovereign country (Iyob 1995). It is an assumption of this paper that the main factors affecting the environment (specifically vegetation) in Eritrea are colonial history, war, economics, drought, deforestation, and soil erosion.

Italian colonization brought about widespread road construction, building of cities (Asmara, Keren, etc.) and agricultural estates. It is an assumption in this paper that the construction during the colonial period was completed at the expense of forestlands and indigenous owned lands (Wrong 2004). Improved capacity for communication associated with transportation must have caused forest land to be converted to urban and agricultural areas. Ethiopian occupation of Eritrea seemed to have increased environmental degradation due to bad governance and war. Although some steps were taken by the Ethiopian government during the 1980s to decrease the rate of deforestation through soil and water conservation terraces and reforestation programs, they were not effectively done. The other reason, the war for independence, increased the cutting of trees to built trenches as well as use of fuel wood for soldiers.

The highest rates of deforestation seemed to have occurred from 1961 to 1991, and also from 2000 to the present. For Eritrea, the most devastating geopolitical and economical problem was the war with Ethiopia from 1998-2000, when the two nations fought over a disputed border area. The two countries agreed on a ceasefire in June 2000, after both sides agreed in Algiers that the border be delineated by the UN boundary commission (Wrong 2004). The issue is still not solved because Ethiopia refused to accept the decision reached by the commission and Eritrea is unwilling to compromise. In Eritrea, approximately 300,000 soldiers (10% of the total population) are in a high alert condition (war with Ethiopia) and many more are being sent to the army; per capita, Eritrea has one of the largest armies in the world. The war directly affected (and is still affecting) the environment in several ways. First, many trees are being cut to supply the army for fuel. Second, trees were and are being cut to build trenches and structures that provide shelter from air missile (bomb) strikes. Third, the army's concentration along the Eritrea-Ethiopia border increases the deforestation rate in one of the relatively heavily forested areas (e.g. in the Gash area along the southwestern border with Ethiopia). War also indirectly affects the environment by allocating resources to military defense, rather than to environmental remediation (e.g. reforestation), and by creating a system where many people (soldiers) use wood fuel who would not normally use it.

From 1990 to 2000, forest cover decreased in Eritrea by 0.3%, and in 2000, forests covered 13.5% of all Eritrean lands (Butler 2001). This is contrary to expectation as the Eritrean government has been conducting a much more intensive reforestation program since its independence from Ethiopia and also due to the non-occurrence of drought from 1990 to 2000. The reforestation program intensity is well portrayed by the forceful recruitment of almost all high school students in Eritrea for two months every year to construct soil and water conservation structures and plant tree seedlings.

Drought may also have affected vegetation change in Eritrea since 1980. The drought periods in 1983-1984 and the four consecutive years of drought from 2000-2004 have negatively affected the vegetation cover and decreased the amount of wood available for fuel consumption (Rock 1999 and Kifle 2003). It should be noted that drought is not a new phenomenon in Eritrea. In the late 19th century, for example, the most commonly referred to drought, "Zemen Akahida" (a tigrigna word which means "Era of Treachery"), had a disastrous impact on the population.

The use of shrubs and trees for fuel is one of the main factors affecting the deforestation rate. As a result of increased fuel consumption, the rate of erosion has increased due to the lack of vegetation cover and associated exposure of the soil to rain and wind. Preliminary results from an economic model that estimated the costs of agricultural production for a 100-year period demonstrated that Eritrea could run out of food by 2007, primarily due to deforestation and erosion (Beal 2004).

Mapping vegetation in Eritrea could help in assessing the rate of vegetation change. Vegetation maps can be used to achieve several goals:

- To measure biodiversity
- Manage drought indices
- Improve agricultural productivity
- Monitor reforestation or forestry activities
- Help make policies in land use planning

The general objective of this study was to map and analyze the causes and consequences of vegetation change in Eritrea over 14 to 16 year periods using Landsat TM and ETM+ data. Some of the specific objectives were:

- Classify vegetation into desert, highland shrub and forest classes using three remote sensing vegetation indices, namely NDVI (Normalized Difference Vegetation Index), SAVI (Soil Adjusted Vegetation Index) and TC Greenness obtained from processing satellite imagery data.
- Map areas where there has been change (decrease or increase) in vegetation from 1984, 1985 and 1986 to 1999, 2000, and 2002 using remote sensing vegetation indices, namely NDVI (Normalized

Difference Vegetation Index), SAVI (Soil Adjusted Vegetation Index) and TC Greenness, and also examine influences on vegetation change.
- Analyze whether there is a significant difference among the three remote sensing vegetation indices.

Some of the assumptions that are inherent in this research are:

- Vegetation values obtained from vegetation indices are higher for forest areas than highland shrubs which are also higher than desert areas.
- The effect of shadows (due to complex topography) in mapping vegetation using remote sensing is negligible.

The data obtained from the research can be used to:

- Make better land management practices, such as reforestation programs and soil and water conservation programs.
- Aid in determining how to use remote sensing data to analyze vegetation.

Vegetation trends in Eritrea are worthy of study because 1) the area has received very little attention, 2) it has experienced a series of droughts and wars that may have affected vegetation and 3) its Sahelian climate, highland topography and proximity to the Red Sea provide the conditions for a wide range of vegetation types, human population densities, and interaction between humans and vegetation.

1.1 Vegetation Indices

Vegetation indices such as NDVI, SAVI, and Tasseled Cap are used to detect vegetation from information collected by satellite sensors. In order to fully understand the remote sensing processes in vegetation mapping, one has to identify the spectral characteristics of vegetation. Plants have a high rate of scattering of electromagnetic radiation due to the high difference in refraction rate between the water rich cell contents and the intercellular air spaces (Ray 1994). The Near Infrared (NIR) spectrum, in the wavelength range of 700nm to 1300nm, is the most important portion of the electromagnetic spectrum for analyzing vegetation because plants appear very bright (high reflectance) in this range (Figure 1.1). Plants appear dark from 400nm to 700nm and also from 1300nm to 2500nm (except for a slight increase in reflectance at 550nm). Therefore, several vegetation indices have been developed to measure vegetation attributes using NIR radiation.

Vegetation indices for remote sensing have been under development for 35 years. Jensen (2000, 2005) outlines the development of the earliest vegetation index from the Simple Ratio in 1968, NDVI (Normalized Difference Vegetation Index) in 1974, the Tasseled Cap Transformation in 1976 and 1979, SAVI (Soil Adjusted Vegetation Index) in 1988, to the most recent developments such as VARI (Visible Atmospherically Resistant Index) in 2002 and NDBI (Normalized Difference Built-up Index) in 2003.

Three vegetation indices will be used for this research: NDVI, SAVI and the Tasseled Cap. These indices were chosen because:

- NDVI is the most commonly used vegetation index, and because previous studies of vegetation in Eritrea and associated regions can be compared using the NDVI index.
- SAVI has an advantage over NDVI in that it considers the effect of soil (Huete 1988, 1991). Comparison among NDVI, SAVI and other indices in relation to atmospheric correction and vegetation cover features is shown in Tables 1.1 and 1.2.
- Tasseled cap has the ability to discern earth features (including vegetation) at a higher detail because it uses a combination of seven bands rather than only 2 bands as with the NDVI and SAVI.

For areas with low vegetation cover, SAVI is much better than NDVI (Ray 1994). Table 1.2 shows Ray's (1994) use of the amount of vegetation cover to choose an index for best analyzing vegetation. Along with vegetation cover amount, atmospheric correction can also be used as an indicator for which index is the best (Huete and Liu 1994, Ray 1994).

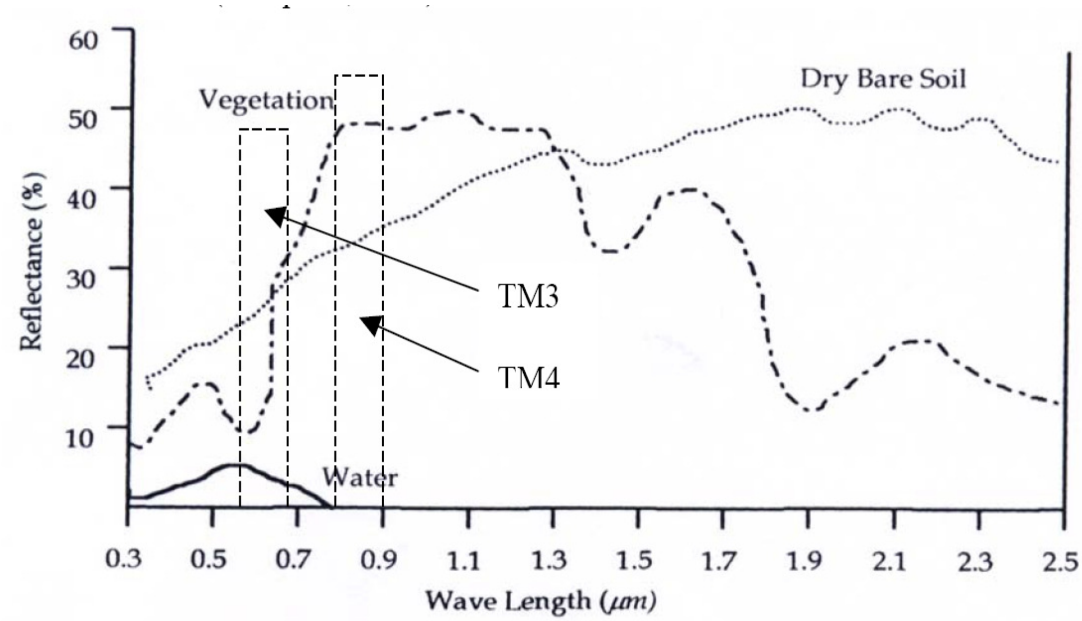

Figure 1.1 Vegetation reflectance wavelength relationship with landsat TM sensor (Source: Hinderson 2004)

Table 1.1 Comparison among selected vegetation indices in relation to atmospheric correction (as adapted from Huete and Liu (1994)) showing that NDVI is the least recommended while SAVI and MSARVI are recommended.

		Total atmospheric correction	Partial atmospheric correction	No atmospheric correction
Best to use rate	Best	SAVI and MSARVI (Modified Soil and Atmospherically Resistant Index)	SARVI (Soil and Atmospherically Resistant Index) and MSARVI	SARVI
	Worst	NDVI and ARVI (Atmospherically Resistant Index)	NDVI and ARVI	NDVI and ARVI

Table 1.2 Comparison among selected vegetation indices in relation to vegetation cover (as adapted from Ray (1994)) shows that NDVI is the least recommended while SAVI is recommended for low vegetation coverage as in most of Eritrea.

Vegetation Index Type	Percentage of Vegetation cover
RVI (Ratio Vegetation Index), NDVI, IPVI(Infrared Percentage Vegetation Index)	30%
SAVI, MSAVI1, MSAVI2	15%
DVI (Difference Vegetation Index)	30%
PVI (Perpendicular Vegetation Index), WDVI (Weighted Difference Vegetation Index) ,GVI (Green Vegetation Index)	15%

1.2 Regional (Sahelian) Vegetation Mapping Using Remote Sensing

While it also has its own unique climatic patterns, the Eritrean landscape is characteristic of Sahelian environments. Therefore, studies from Sahelian environments might be able to explain vegetation and moisture patterns in Eritrea. This section reviews some selected remote sensing research conducted in the Sahel from 1990 to 2004 to provide guidance on how to proceed with the methodology and analysis in Eritrea.

The use of remote sensing to study vegetation should be validated using ground and climate data to increase the reliability of the results. Remote sensing provides data on rainfall patterns using satellite imagery. The ensuing results can be used in conjunction with ground data (rain gauges) from local areas for more reliability. Pietroniro et al (1990) used such a method with 1986 data from ORSTOM (L'Institute Francaise pour le Development par Cooperation) for Meteosat (visible and infrared bands) and rainfall data from 142 stations in the Sudan-Sahel distributed over the whole study site. The use of Meteosat is very good as it has a high temporal resolution (every ½ hour). It also provides a good alternative to using rain gauges as they are localized and extrapolation may not be accurate over larger areas. However, middle infrared bands might better explain the moisture content rather than the visible and infrared bands used by Pietroniro et al (1990). This may be possible if they could integrate their data with other sensors such as Landsat and use vegetation indices such as the Tasseled Cap.

Most of sub-Saharan Africa has faced substantial drought and famine periods. Eritrea has faced drought several times. The country is currently experiencing its fourth consecutive drought since 2000. Hutchinson (1991) examined remote sensing based early warning systems (EWS) and proposed better solutions to improve issues with EWS. All the objective issues were analyzed using qualitative analysis. In assessing the general status of EWSs, the authors considered ground data and satellite derived data. In the ground data methodology, a brief discussion regarding rainfall and temperature, crop yields, food stocks, food and animal prices, health and nutrition status, aerial photography, and other observations (use of special teams or assistance personnel) was included. In the satellite derived data methodology, a brief discussion of rainfall estimates, vegetation condition, cropped area, forage production and crop yield models, water balance, and crop yield and production was included. The situation in EWSs in Africa was assessed briefly by considering operational systems and experimental systems. The operational systems discussion included analysis of regional AGRHYMET (agriculture, hydrology, meteorology reports from centers), FEWS (famine early warning systems), and GIEWS (Global information and early warning systems). In the experimental systems issues, the authors described how CSE (Centre de Suivi Ecologique) uses AVHRR (Advanced very high resolution radiometer) images to study vegetation in Senegal, and also the works of ESPACE (Evaluation et suivi de la production agricole en fonction du climat et de l'environment) in Senegal and Mali; GIMMS (Global Inventory Monitoring and Modeling Studies); ILPP (Integrated Livestock Production Project); and SRN (Surveillance de resource naturelle). The author also mentions that there is no reliable relationship between NDVI and crop assessment.

Holben et al. (1991) examined the effect of aerosols in relation to vegetation remote sensing, atmospherically corrected satellite images and computed NDVI (Normalized Difference Vegetation Index) maps. The authors used NOAA AVHRR (advanced very high resolution radiometer) images and a reference instrument (sun photometer) to obtain and validate data. The study areas (where the sun photometers were located) were in Mali (Youwarou, Niono, Sevare, Gossi, Gao, Bamako, Hombori), Niger (Tahoua, Bilma, Agadez, N'guigmi, Zinder) and Senegal (Dakar). It was ensured that no clouds restricted the photometer's view of the sun during data collection. It was found that there was no significant diurnal variation in aerosol effect on vegetation remote sensing, but there was significant variation between seasons (especially during the high rain periods).The authors also used (as will be used in the statistical analysis in this paper) the coefficient of variation, rather than mean or standard deviation, which seems ideal as it differentiates between values at the higher and lower ends.

Souflet et al (1991) also looked at the effect of the atmosphere in the use of vegetation indices, and presented a method for correcting atmospheric effects (scattering and absorption). The authors used a combination of ground data (for atmospheric thickness), NOAA-9 (AVHRR), NDVI, climate data, and a correction algorithm function using "the actual bidirectional surface reflectance and mean angular reflectance" to get ground albedo values. Their assumption that aerosols are spheres is questionable and calibration issues in the sensors might have contributed to some of the errors (the authors also mentioned these as a possible limitation).

Huete and Tucker (1991) assessed the effect of soil brightness or interference in measuring vegetation indices. The authors stated that in canopy covers of 40-75%, "moistening the soil surface underneath such canoipies can increase the NDVI values by 25%." The authors focused on NDVI imagery derived from AVHRR data. Ground and aerial photography based measurement of spectra were also used for the analysis. The authors stated that NDVI, PVI (Perpendicular Vegetation Index), and SAVI can be used reliably at the global level (large scales) relative to soil influences, and that with the increased capability to correct for atmospheric effects (scattering and absorption), PVI and SAVI are the better alternatives.

Fuller (1998) examined the trend in NDVI in Senegal. The methodology used was a combination of seven years of NDVI data, AVHRR high resolution Picture Transmission (HRPT), crop harvest data and a phenology and land cover map. The integration of ground harvest data along with the trends in maximum NDVI values is a reliable technique to use as the growing season is short and highly coupled with the crop growth period. However, the use of NDVI may not be ideal, especially because the author used the maximum NDVI, which coincides with high rainfall season, which in turn corresponds to wetter soil and thus might artificially increase the value of NDVI (recall that soil differences are not taken into account with NDVI) (Huete and Tucker 1991).

Larsson (2002a) analyzed changes in the acacia cover using satellite imagery in the Rawashda Forest Reserve, Kassala Province, Sudan. Three radiometrically and geometrically corrected Landsat MSS images from different dates (11 December 1972, December 17 1979, and 29 January 1990) were used. NDVI was used as a measure of vegetation cover. The forest cover percent was found to have increased in 1990 relative to 1979. Larsson (2002b) also examined land cover and vegetation changes in Kassala, Sudan. Nine radiometrically and geometrically corrected Landsat MSS images from different dates (24 November 1972, January 31 1979, and 4 January 1987, 3 February 1973, 8 February 1979, 12 December 1989, 11 December 1972, 17 December 1979, and 29 January 1990) were used. Unlike the previous paper by the same author (where NDVI was used), a supervised maximum likelihood classification method (using three to four training sites) was used. Accordingly, sandy land coverage did not show significant increase or decrease over the time periods, while grasslands decreased and cultivated areas increased. The use of training sites for validation, the analysis of the limitations of the methodology, and the method of classification increased the reliability of the paper. However, the number of training sites (three to four) seems very low compared to the total study area (54,263km^2). Also, the three different dates from the Landsat images did not match exactly. An explanation of the inherent intra-seasonal variation and its effect on the data analysis would have made the paper better. This may be a hurdle, though, as Landsat has a relatively low temporal resolution.

Twumasi et al. (2003) examined rangeland issues in three Sahelian regions (Burkina Faso, Mali, and Niger) over a decade temporal scale. The authors used Landsat TM and ETM+ data and the Tasseled Cap transformation to achieve the intended goals, rather than AVHRR as most other studies do. The use of Landsat TM and ETM+ provides a better spatial resolution for the Sahel than AVHRR. The use of the Tasseled Cap transformation was also ideal as it considers various environmental attributes, such as the soil, and uses the relationships among the seven bands, which allows the technique to give finer spectral resolution results. However, the authors used Landsat TM and ETM+ data from different dates that did not match (October 1987, and September 1999; November 1986 and October 2001; and November 1984 and October 2001). The incompatibility of the dates may have contributed some error, especially as the intra-seasonal variation in the Sahel is high. Landsat data also have a low temporal resolution.

Budde et al. (2004) also assessed the use of higher resolution NDVI to examine productive and non-productive (degraded) lands in Senegal (West Africa). The authors used AVHRR, Landsat TM, and SPOT sensors. They also used NDVI as a vegetation index measure. The use of AVHRR, which provides high temporal resolution, and SPOT data, which provides high spatial resolution, increased the validity of the results. The integration of NDVI derived from AVHRR (1992, 1993, and 1995) data and SPOT (1998-2001) data was not stated clearly. Therefore, the NDVI derived from AVHRR might be different from SPOT and Landsat and might therefore affect the result. This difference among the instruments is due to differing spectral, spatial, and radiometric resolutions. The use of NDVI may have not been reliable as it does not address the influences of soil or shadows. The use of the standard deviation as a threshold might have been appropriate for one image, but not for two or more data sets with different time periods. The use of the coefficient of variation might have been better as it is not influenced by the NDVI values variation in the study area.

In an analysis of Kordofan, Sudan, Hinderson (2004) showed that NDVI and precipitation have low correlation. The explanation given is that cropping areas might have increased with population increase, and also 1984 was a drought year while 1988 was not. Sjöström (2004) found that "values for annual rainfall compared to annual NDVI are significantly but weakly correlated". This pattern shows similarities to intra-annual differences in Eritrea and indicates that the variation in rainy periods and seasonality of crops and grasses make NDVI analysis difficult.

1.3 Vegetation Mapping in Eritrea and Gap Analysis

Assessing previous studies dealing with remote sensing of vegetation in Eritrea sheds light on the purposes of this paper. Analysis of gaps in these studies will help define research questions and issues that have not been previously addressed, thereby helping to define the objectives of this paper. Vegetation mapping depends on the difference between vegetation types. Vegetation types are affected by different ecological zones, which are in turn dependent on rainfall, temperature, topography and altitude, and distance from water bodies (such as the Red Sea in the case of Eritrea). There are six ecological zones in Eritrea. These are (starting from the east on the red sea coast), the Coastal Plains, the Eastern Escarpments, the Central Highlands, the Western Lowlands, the Southwestern Lowlands, and the North Western Lowlands (Figure 1.2).

The Eritrean geology and topography is quite variable. The majority of Eritrea is characterized by “the metamorphic basement, belonging to the Arabian Nubian shield” (Heldal and Yohannes 2000). Dominantly sandstone Mesozoic sediments are found in the central highlands around Asmara, (Jones 1991). The elevation (topography) also varies from the low elevation areas in the coastal plains, then rapidly rising areas of the eastern escarpment zones to the plateaus of central highland zones and then to the gently decreasing in elevation on the western escarpment zone and finally to the western lowlands (Jones 1991 and USGS).

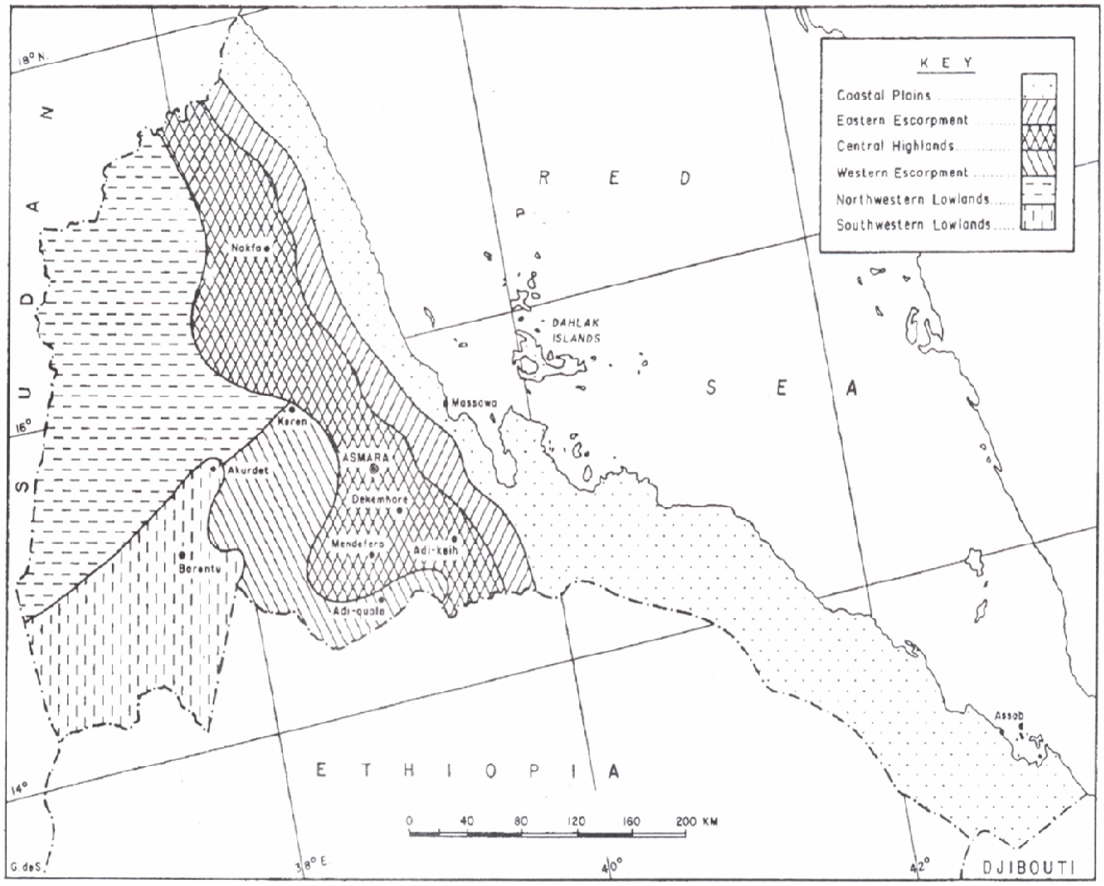

Figure 1.2 Agro-ecological Map of Eritrea where the majority of the Eastern Escarpment composed of forest areas, the South western lowlands is composed of forest, shrub and dry savannah grassland, the Central Highland and Western Escarpment is mountainous and characterized by shrubs, the North Western lowland is highly semi-arid, and the Coastal Zone is desert (Map source: Negassi et al 2000).

Very few studies have mapped vegetation using remote sensing data in Eritrea. The most significant studies are those by Woldu (unpublished thesis: 1997) and by his academic advisor Van Buskirk (unpublished internet papers 1998 and 2001). Other works also include by the Metrological Services of Eritrea (2004) and Zinner et al (2001).

The objective of Woldu's thesis (1997) was to perform a preliminary analysis of the applicability of remote sensing techniques for biomass, radiation and rainfall estimation in Eritrea. AVHRR data were used (1km by 1km resolution) to map and analyze NDVI. More images were obtained from the Meteorological data of the civil aviation department in Eritrea and the Image Display and Analysis (IDA) software facility was used. Atmospheric effects (including cloud contamination) were corrected in the study. Other corrections were made as there were geographically shifted images with locations having erroneous latitude and longitude, there was noise in images (some pixels had unusually high NDVI values) and there was also screening of large areas by a cloud mask. Consequently, the thesis produced biomass maps using NDVI and no ground based data (using mathematical formulas some ground data were simulated from similar study area in West African Sahel). Estimation of biomass yield and radiation maps (obtained using images from Meteosat and also ground data containing relative humidity, temperature, rain, wind direction, and wind speed in addition to the radiation for each station) were also made. Woldu's research analysis was also improved by the production of rainfall maps from historical data.

Van Buskirk (unpublished internet information, 1998, 1999, 2000, 2001, and 2003) provided NDVI from AVHRR (Figure 1.3) images as well as topography, rainfall, and population maps with some ground data. His maps show that the highest NDVI values were found in the Gash and Eastern escarpment areas. Other related maps and data relevant to analyzing vegetation trends and mapping were the Annual Average Solar Radiation, temperature maps (using AVHRR Channel 5 thermal infrared images), temperature map index (Daily average, daily minimum, daily maximum), and potential temperature map index (Daily average, daily minimum, daily maximum).

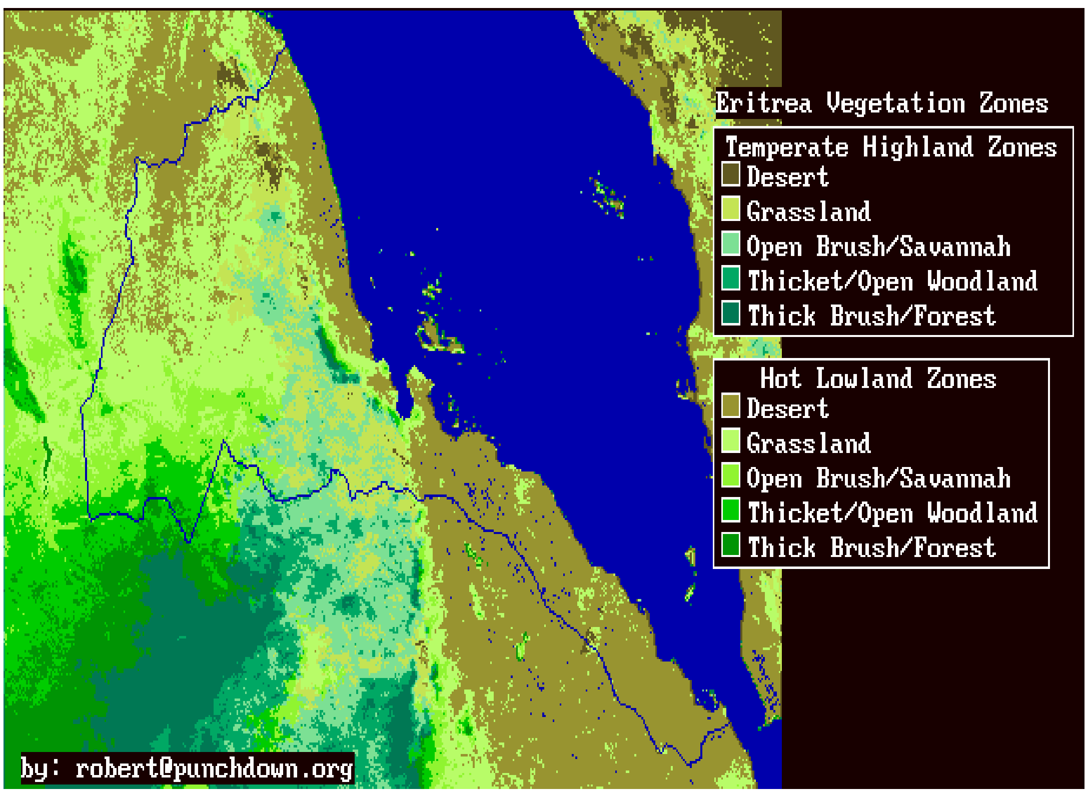

Figure 1.3 Eritrea vegetation zones by Van Buskirk (1998) where Eritrea was divided into two categories depending on agro-climatic (temperature) zone. Each of these two is again divided into five more vegetation classes. Desert areas were found in the Coastal and North Western zones, while the forest areas were found in the Eastern Escarpment as well as the southern fringes of the Southern Lowland zones.

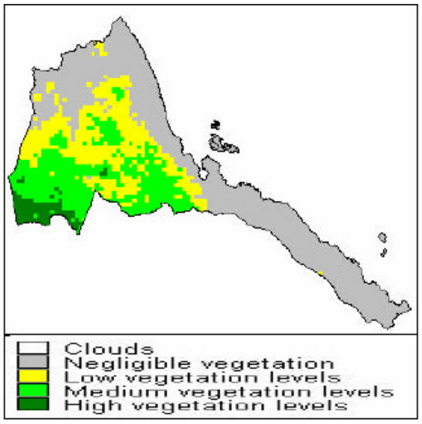

Figure 1.4 Vegetation map for August 1999 (Source: Meteorological Services of Eritrea 1999).

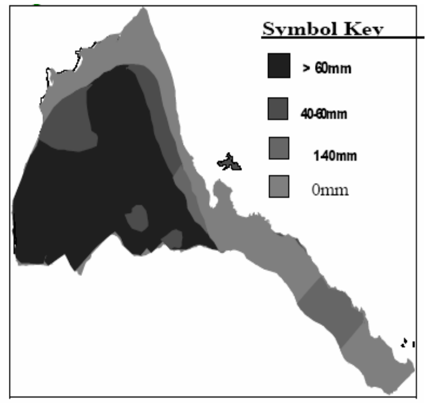

Figure 1.5 Distribution of rainfall for August 1999 (Source: Meteorological Services of Eritrea 1999).

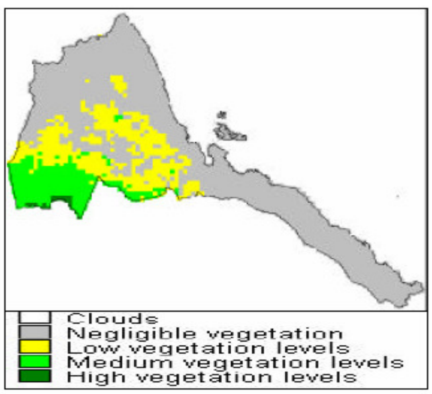

Figure 1.6 Vegetation map for July 1999 (Source: Meteorological Services of Eritrea July 1999).

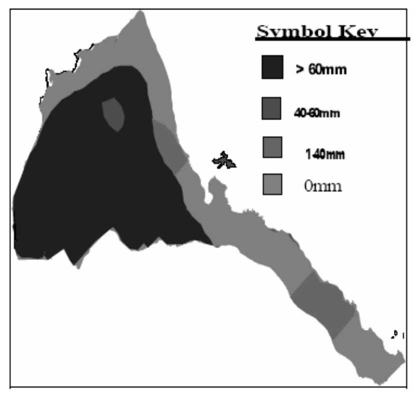

Figure 1.7 Distribution of rainfall for July 1999 (Source: Meteorological Services of Eritrea 1999).

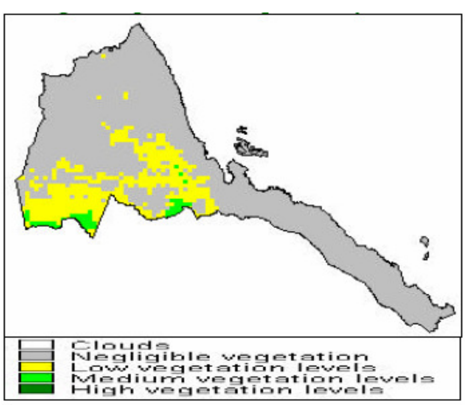

Figure 1.8 Vegetation map for July 2000 (Source: Meteorological Services of Eritrea July 2000).

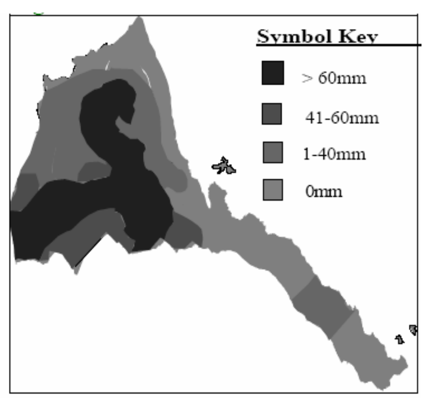

Figure 1.9 Distribution of rainfall for July 2000 (Source: Meteorological Services of Eritrea July 2000).

The Meteorological Services of Eritrea produced NDVI vegetation maps obtained from AVHRR images, which indicated that that there might be a positive correlation among NDVI values and rainfall amount in Eritrea (Figures 1.4 – 1.9). The figures also indicated that there was a marked decrease in NDVI values in 2000 from those of 1999. The lower amount of rainfall in 2000 relative to 1999 might have been due to the onset of drought. Several papers suggest that the Sahel region showed signs of recovery from the drought in mid-eighties (Eklundh 2003, and Sjöström 2004). It appears that 1998 was a wetter year than 1999 in general (compiling both the August and July months) with the exception of Elabered and Agordat stations (Figures 1.10 and 1.11). Thus in this paper, it is expected that vegetation might have increased in 1999 and perhaps decreased in 2000, relative to vegetation in the mid-eighties.

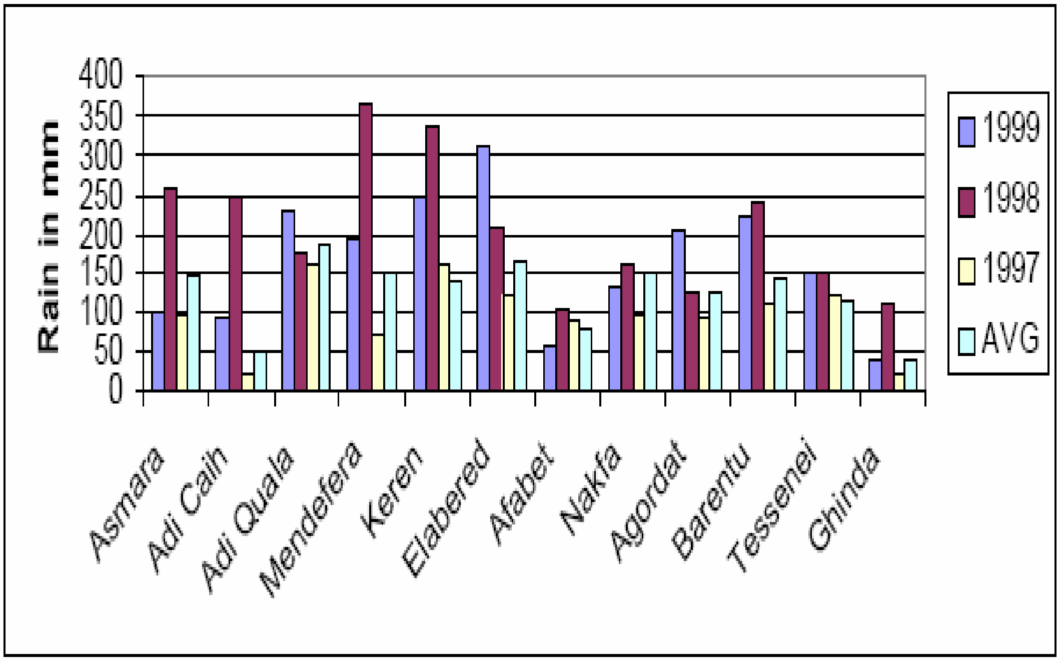

Figure 1.10 Comparison of monthly rainfall in August 1999, 98, 97, and long year average for Eritrean cities, where in most of the stations, 1998 was generally a wetter year than 1999. (Source: Ministry of Agriculture 1999).

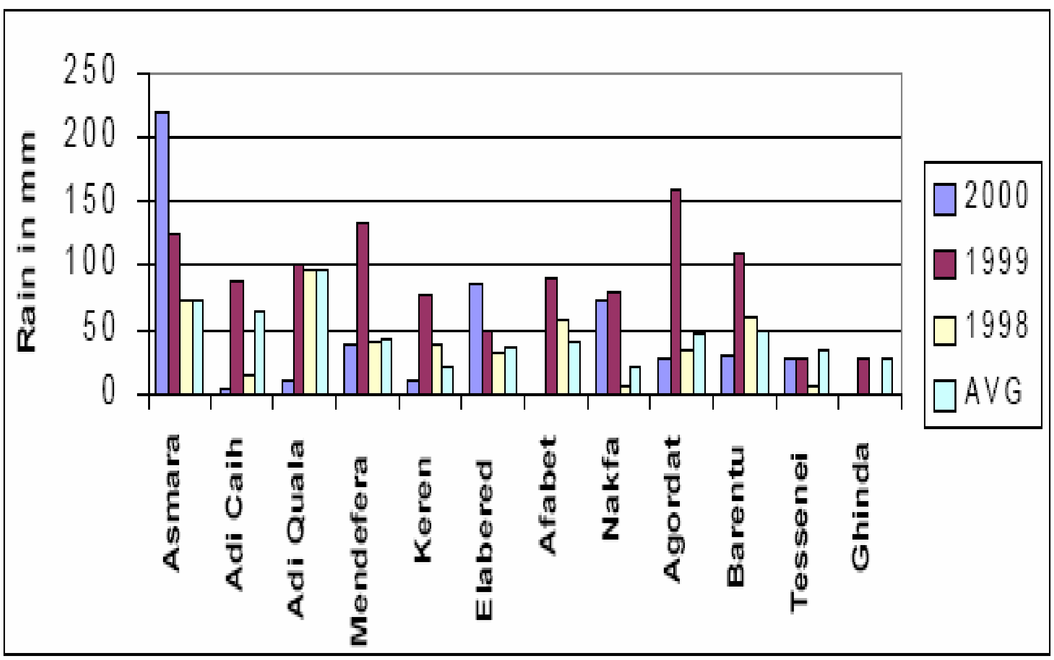

Figure 1.11 Cumulative rainfall during Dekad 21(21-31 July) 2000 and long year average in Eritrean cities, where 1999 was generally the wettest year followed by 1998 with the exception of Asmara in 2000. (Source: Ministry of Agriculture 2000).

This research will fill in some gaps left by previous studies that mapped vegetation changes in Eritrea, as well as contribute some analysis and data for remote sensing science. Below are statements showing gaps filled by the results and discussions in this paper in the use of remote sensing to map vegetation trends in Eritrea:

- The last updated vegetation index maps were made in 1998, seven years ago. More analysis could be done on the post 1998 times.
- Most of the vegetation mapping (using remote sensing) did not analyze changes spatially and temporally. This study intends to analyze spatial and temporal changes.
- No vegetation indices other than NDVI seem to have been used. This paper will use SAVI and TC Greenness.
- Previous studies in Eritrea appear to have used IDA software only. In this paper an updated software, ENVI 4.0 (The Environment for Visualizing Images), which is more current than IDA will be used. The advanced features in ENVI might give a different result.
- Only AVHRR (1km by 1km resolution) was used in previous works by both Buskirk (1998) and Woldu(1997) in remote sensing vegetation studies in Eritrea. In this paper, a different sensor with higher spatial resolution, Landsat TM and ETM+ (30m by 30m resolution), has been used.

2 METHODOLOGY

2.1 Study area

The study areas were taken from eight spatially and temporally paired (16 single images) Landsat TM and ETM+ images in Eritrea (Table 2.1, Figures 2.1 and 2.2). Study area 1 (The Highland, Eastern Escarpment and Eastern lowland study area) comprised three agro-ecological zones (namely the Central Highlands, the Eastern Escarpment and the Coastal Plains zones). Study areas 2, 3, 4 and 5 (Denkalia, South Denkalia, Central Denkalia and North East sahel) were found exclusively in the Coastal Plain agro-ecological zone. Study area 6 (West Sahel) was from the North Western Lowlands. And Study areas 7 and 8 were from the western escarpment as well as the central highlands zones (Southern Highlands and Gash Barka study areas).

The elevation of Eritrea is quite varied, but it can generally be divided into two broad categories: the central highlands, which range in elevation from 2000 to 3000 meters above sea level; and the lowlands, both eastern and western, which range in elevation from 0 to 700 meters. Elevation plays an important role in the vegetation pattern in several ways. For example, the mountains in the Eastern Escarpment areas help to bring two rainfall seasons to the area due to the orographic (mountain) effect. Vegetation in the highlands differs from that of the lowland areas due to cooler temperatures, and generally higher rainfall (except when compared to the Gash Barka regions in the southwestern lowlands) among other things (Figure 2.1). The land use pattern also differs from area to area, which affects the vegetation pattern. For example, there is predominantly fishing and nomadic culture in the coastal plains and rain fed farming in the central highlands. Also, there is low population density in the coastal plains and high population density in the central highlands.

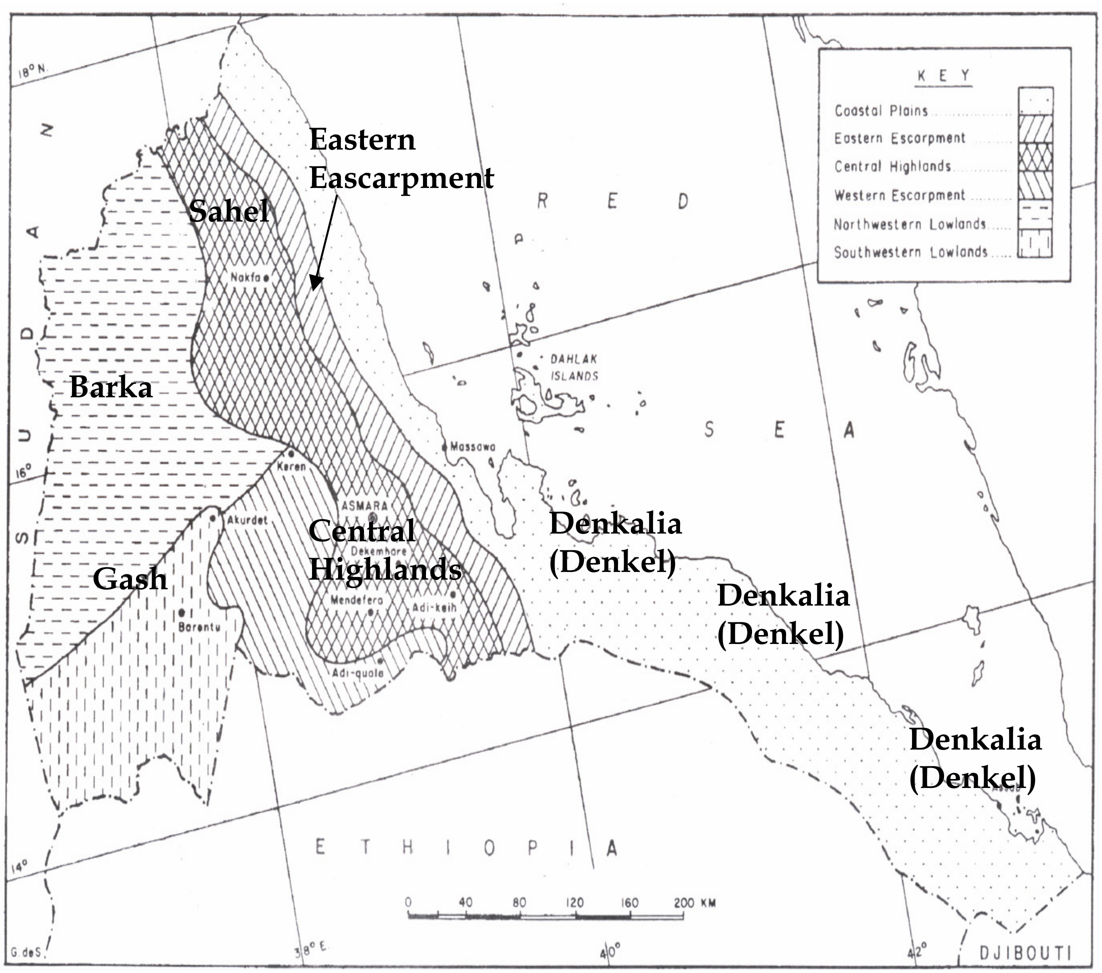

Figure 2.1 : Agro-ecological map of Eritrea (Source: Negassi et al 2000) and some common Eritrean regional place names. The wettest part is the Eastern Escarpment followed by the Southern Gash, Central Highlands, Barka, Sahel, and the driest being Denkalia.

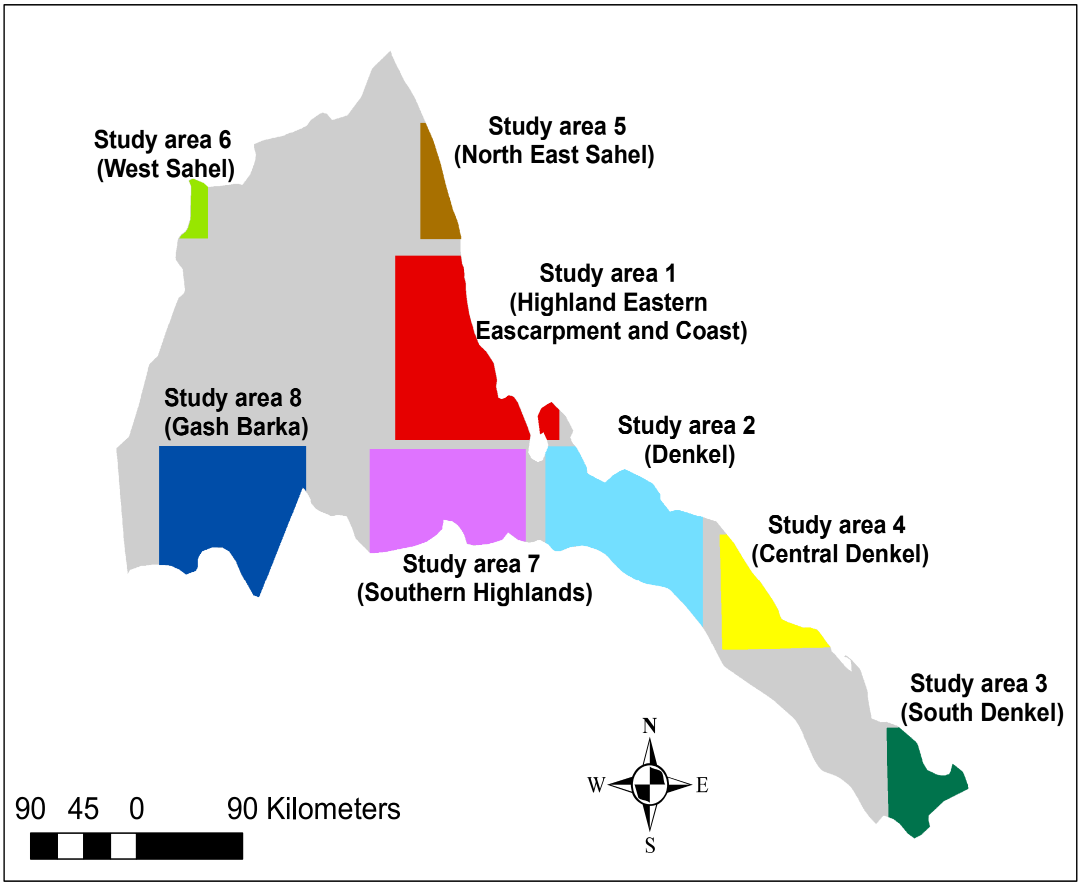

Figure 2.2 Locations within Eritrea of the Eight study areas from Study area 1 (Highland, Eastern Escarpment and Coastal Plains) to Study area 8 (Gash Barka).

Study area 1 (*Highland, Eastern Escarpment and Coastal Plains*) covers 13,188 km^2, and is characterized by flat topography in the east that increases in elevation from sea level up to 2500 m (Fig 2.3). The climate pattern in this area includes three agro-ecological zones: coastal plains, eastern escarpments, and central highlands. Vegetation ranges from that characteristic of the desert to that of the forest to highland shrub-crops (from east to west). The yearly rainfall also varies in each area. The coastal plains had a minimum recorded rainfall of 2.2 mm per year and a maximum of 192 mm per year from 1992-2004 (Meteorological Services of Eritrea, 2004). The eastern escarpment area (as from the proxy data of Ghinda, May Habar, and Embatkala station) recorded a 1992-2003 minimum and maximum rainfall range from 88 mm to 1002 mm per year, respectively. The eastern escarpment area has an altitude ranging from 800 m to 1800 m above sea level (Figure 2.3) and includes the highest (possibly the only) forested area because it gets rain twice a year (bimodal rainfall). The forested area includes species such as *Juniperus procera, Olea africana, Hyphaene thebaica, Tamarix aphylla*, and Acacia woodland, among others (Emerton and Asrat 1998). The central highland area ranges in elevation from 1600 m to 2500 m (Figure 2.3). The vegetation pattern includes large amounts of acacia species as well as cereal crops (barley, wheat, millet etc). The 1992-2004 minimum and maximum recorded rainfall amounts were 233 mm and 689 mm per year, respectively (Meteorological services of Eritrea 2004).

Study areas 2, 3, and 4 (*Denkalia, South Denkalia and Central Denkalia*) cover 10846 km^2, 3444 km^2, and 4179 km^2, respectively. As these three areas are found in the Coastal Plains agro-ecological zone, the minimum and maximum annual recorded rainfall amounts were 2.2 mm and 192 mm per year, respectively, as from proxy data of the Assab station (Meteorological services of Eritrea 2004). There is little variation in topography, which is mostly flat and ranges from sea level (Red Sea) to 400m (Figure 2.3). Population density is very low in the area, which is characterized by pastoral, fishing and trading land use patterns. The area has a desert biome dominated by very sparse short-grasses and shrubs.

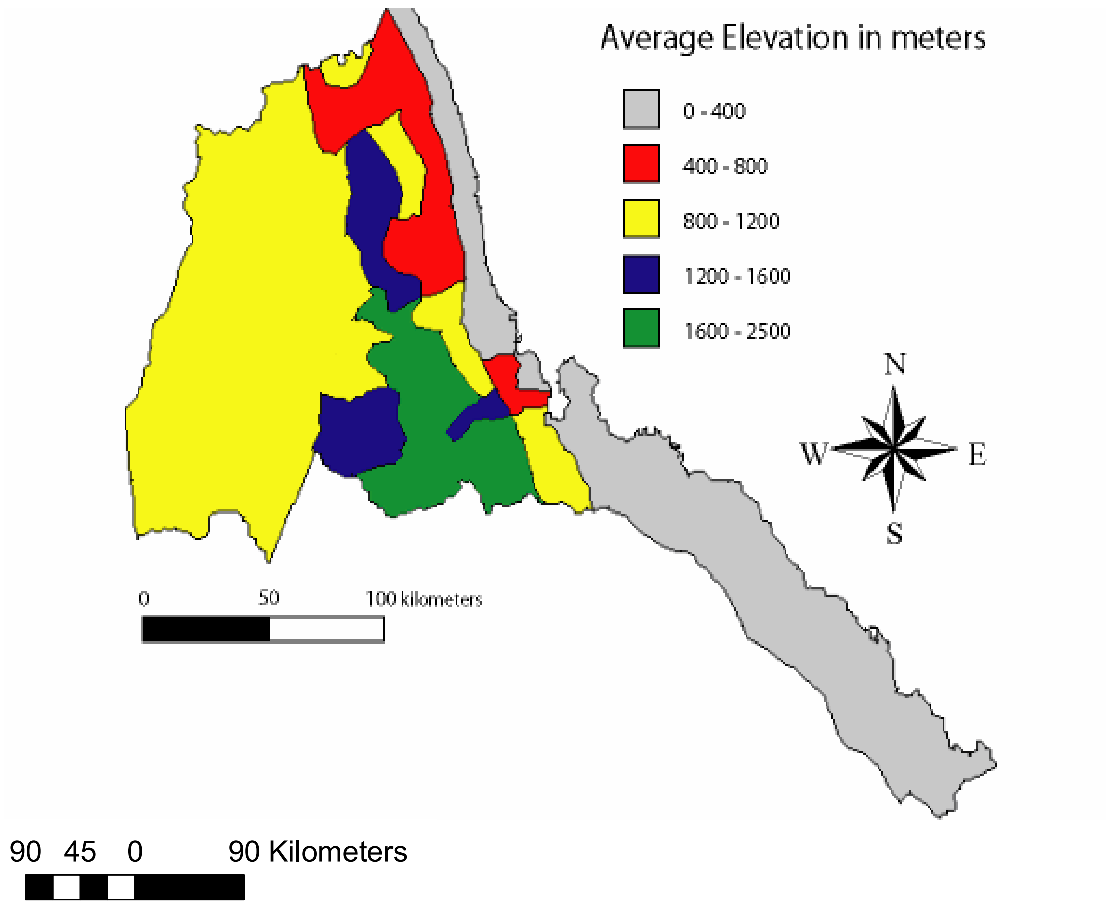

Figure 2.3 Elevation characteristics of Eritrea (adapted from USGS 2004)

Study area 5 (*North East Sahel*: found in the Coastal Plains zone) covers 2063 km^2. The region has topography that is similar to that of study areas 2, 3 and 4 but with a lower population density and a slightly higher precipitation patterns. The minimum and maximum annual rainfall amounts recorded from 1994-2003 were approximately 33mm and 336 mm, as from proxy average data of the Massawa station (Meteorological services of Eritrea 2004). However, some areas such as the southern portions of study area 4, for example, are wetter than study area 5 due to seasonal river flows and irrigation.

Study area 6 (*West Sahel* found in the North Western Lowlands) spans 795km^2 and ranges in elevation from 800 m to 1200 m. The minimum and maximum annual rainfall amounts recorded from 1993-1998 were approximately 33 mm and 336 mm, as from proxy data of the Kerkebet station (Meteorological services of Eritrea 2004). This area is very sparsely populated and the predominant land use pattern is pastoral.

Study area 7 (*Southern Highlands* found in the Western Escarpment and Central Highland zones) spans 10631 km^2 and the region ranges in elevation from 1600 m to 2500 m. The minimum and maximum rainfall amounts recorded from 1993-2004 were approximately 165 mm and 750 mm, as from proxy average data of the Asmara, Afdeyu, Maidema, and Mendefera stations (Meteorological services of Eritrea 2004). Intensive rain fed agriculture is common in the Southern Highlands, allowing for the production of millet, barley, sorghum, and sometimes *Teff eragrotis,* the main grain used to make *injera,* a sponge-like bread that is the staple food for more than 50% of Eritreans (*Teff eragrotis* is mostly imported from Ethiopia). Other vegetation includes *acacia sp*., *Juniperus procera, Olea africana*, and *Eucalyptus spp*.

Study area 8 *Gash Barka* (found in the Southwestern Lowlands zone) covers 12006 Km^2 and ranges in elevation from 800 m to 1200 m. The minimum and maximum annual rainfall amounts recorded from 1993-1998 were approximately 125 mm and 691 mm, as from proxy average data of the Barentu, Shambuko, and Tokombia stations (Meteorological services of Eritrea 2004). Predominant land use patterns are rain fed agriculture and pastoralism. Common vegetation types include many species of acacia, *Juniperus procera,* and *Olea Africana* (Emerton and Asrat 1998).

2.2 Data Collection Method

Sixteen (16) Landsat TM and ETM+ scenes were obtained from the Global Land Cover Facility (2004). These images were paired according to their seasonal (not monthly or diurnal) and location extent match (Table 2.1):

Table 2.1 Spatially and temporally matching Landsat TM, and ETM+ images. These images were already geometrically corrected, and the seasonal match criteria was that the gap between the matching images should not be more than 70 days.

Study Area	Landsat data code	Area name designation	Data acquisition date	Season	Match seasonally & Spatially (yes or no)
Study area 1	012-377	Highland, Eastern Escarpment and Eastern lowland	22-Nov-84	Fall/Winter	Yes
	037-652	Highland, Eastern Escarpment and Eastern lowland	27-Jan-00	Fall/Winter	Yes
Study area 2	012-366	Denkalia	5-Jan-86	Winter	Yes
	037-878	Denkalia	5-Feb-00	Winter	Yes
Study area 3	016-899	Southern Denkalia	9-Mar-86	Spring	Yes
	038-019	Southern Denkalia	13-May-00	Spring	Yes
Study area 4	012-355	Central Denkalia	14-Jan-86	Winter	Yes
	037-805	Central Denklia	3-Feb-02	Winter	Yes
Study area 5	012-376	N.E. Sahel	22-Nov-84	Fall/Winter	Yes
	037-651	N.E. Sahel	5-Jan-00	Fall/Winter	Yes
Study area 6	012-399	West Sahel	1-Jun-84	Summer	Yes
	037-576	West Sahel	13-Jun-00	Summer	Yes
Study area 7	012-378	Southern Highlands	22-Nov-84	Fall	Yes
	037-653	Southern Highlands	25-Nov-99	Fall	Yes
Study area 8	012-391	Gash Barka	3-Jan-86	Winter/Fall	Yes
	037-727	Gash Barka	15-Nov-99	Winter/Fall	Yes

Rainfall (amount, duration and spatial extent) is one of the most important factors that affect the distribution of vegetation in an area. However, problems arose in identifying the effects of rainfall on vegetation. While monthly data were available for 1943 to 1991 (USGS (2000), it was hard to obtain monthly data for 1999 and 2000 pertaining to the study areas. Only cumulative yearly rainfall data were available (Meteorological Services of Eritrea 2004).

2.3 Data Analysis Method

Data analysis included the use of ENVI (Research Systems Inc. 2003), ArcGIS 9.0 (ESRI Inc. 2004), and S-Plus 6.2 (Insightful corp. 2002) software packages. ENVI was used to load the Landsat images and calculate the different vegetation and wetness indices. Geometric correction was not required as the images were already corrected, but resizing of datasets were done to match the extents of the TM and ETM+ data. All of the images were converted from radiance data to reflectance data as outlined by Chander and Markham (2003). The data were also atmospherically corrected using the dark pixel subtraction method (Chavez 1988). Results from the analysis of the remotely sensed data were integrated with rainfall and land use planning issues in the discussion.

For classifying vegetation into desert, highland shrub and forest classes (the first objective), observation, comparison to the agro-ecological zones of Eritrea, and personal experiences were used to obtain the ranges of TOA (Top of the atmosphere or reflectance) values for each of the three indices (Table 2.2).

Table 2.2 Vegetation class limits for the different vegetation indices.

	Vegetation Values			
	NDVI	SAVI	TC Greenness	Depicted Color
Desert	(-1.00 - 0.16)	(-1.00 - 0.11)	(-1.00 - 0.035)	Yellow
Highland Shrub	(0.17 -0.27)	0.12 - 0.22)	(0.036 - 0.072)	Pale green
Forest	(0.28 - 1.00)	(0.23 - 1.00)	(0.073 - 1.00)	Dark green

For mapping vegetation change (second objective), three different vegetation indices and two different moisture indices were calculated for each of the eight paired (16 data sets) study areas. The difference between the paired data sets was also calculated using the band math function in ENVI. The mathematical equations used for NDVI, SAVI, and TC Greenness were:

$$NDVI = \frac{NIR - R}{NIR + R}$$

$$SAVI = \frac{(1+L)\ (NIR - red)}{NIR + red + L}$$

Where:
NIR = Near Infrared band (band 4)
R = Red band (Band 3)
L= soil correction factor = 0.5
b1, b2… b7 = Landsat TM and ETM+bands
Source; Jensen (2005)

Tasseled Cap Greenness (TC Greenness) =
(b1*(-0.1603))+(b2*(-0.2819))+(b3*(-0.4939))+(b4*(0.794))+(b5*(-0.0002))+(b7*(-0.1446))

The mathematical equations used for MSI (Moisture Stress Index) and TC Wetness were:

$$MSI = \frac{\text{Band 5}}{\text{NIR}}$$

Where:
NIR = Near Infra red band
Band 5 = of Landsat TM or ETM+
b1, b2… b7 = Landsat TM and ETM+bands
Source; Jensen (2005)

Tasseled Cap Wetness (TC Wetness) =
(b1*0.0315)+(b2*0.2021)+(b3*0.03102)+(b4*0.1594)+(b5*(-0.6806))+(b7*(-0.6109))

The differences in vegetation indice vegetation values between pairs of images was done using the ENVI's band math function. The percentage change in the vegetation reflectance value per unit area in km^2 and by vegetation classes (desert, forest, and highland shrub) was used to assess the rate and spatial pattern of vegetation change using the NDVI, SAVI, and TC Greenness. MSI and the TC Wetness were used to assess the effect of moisture stress or wetness on vegetation using only the percentage change and visual observation (as portrayed by the three vegetation indices). The images processed using ENVI were transferred to ArcGIS 9.0 for three purposes: 1) although ENVI has the capability to mask images, GIS does it less tediously, and thus was used for this purpose. 2) ArcGIS was used to calculate the areas of the images in km^2. 3) ArcGIS has better mapping capability than ENVI, and it was therefore used for map making. The vegetation change rate, standard deviations, and mean vegetation values were also obtained for each study area using ArcGIS after areas unrelated to the study (such as the Red Sea, Sudanese Lands, and Ethiopian Lands) were clipped out. The coefficient of variation (which is the standard deviation divided by the arithmetic mean) was also used to estimate the variability of values within the images and was calculated by dividing the standard deviation by the mean (Ramsey and Schafer 2002).

To investigate the third objective (whether there is any difference in using the three vegetation indices), the percent change in vegetation cover for each of the study areas was used. Tukey's multiple comparisons ANOVA (fixed effect) was used to compare the percentages among vegetation indices to determine whether there was any significant difference among the different indices. The comparison of the vegetation indices was done at two scales, large and small. The large scale assessment was done by assessing the decrease in percentage conveyed by the three different indices for the entire area of each of the eight study areas. The small scale assessment was done by taking thirty two samples using subjective sampling method from study area 1 (Highland Escarpment and Coastal area).

3 RESULTS

3.1 Vegetation Classification Using NDVI, SAVI, and Tasseled Cap Greenness

Vegetation in the eight study areas was classified as desert, highland shrub, or forest. The classification was based on agro-ecological zone data and and experiences of the author (Table 2.2 and Figure 1.1). Using such subjective bases, vegetation classes were created (Figures 3.1, 3.2 and 3.3 and Table 2.2). Classification results varied among the three vegetation indices (as the areas of vegetation increase and decrease in the three vegetation biomes also differed among vegetation indices, as shown in section 3.1).

In study area 1, all three indices showed desert vegetation class dominance (Table 3.1 and Figures 3.1, 3.2 and 3.3). There was a difference in the classification of vegetation among the three indices. NDVI and SAVI classifications of the highland shrub and desert areas were noticeably similar (but not for the forest class), but these two indices produced a classification different from that of the TC Greenness.

Table 3.1 Vegetation Classification (January 27, 2000) for study area 1 (Highland, Eastern Escarpment and Coastal Plains), where by all the three indices showed the dominance of the desert vegetation class. Note that both NDVI and SAVI gave similar results (with the exception in forest class) while both differing with TC Greenness.

	Percent Change in Vegetation		
Vegetation Classifications	NDVI 2000	SAVI 2000	TC Greenness 2000
Desert	53	56	71
Highland shrub	32	37	21
Forest	15	7	8
	100.00	100	100.00

The results obtained for study areas 2, 3, 4, 5 and 6 were similar, showing that most of their area was classified as desert. There was no noticeable difference in classifying vegetation among the three indices in these areas (Table 3.2 and Figures 3.43, 3.44, and 3.45). The average value per percentage of vegetation coverage per study areas per vegetation indices obtained is shown below.

Table 3.2 Vegetation Classification for average vegetation index values for study areas 2, 3, 4, 5, and 6, where there was a high dominance in the desert class. Note that there is no noticeable difference in the classification system among the three vegetation indices.

	Average vegetation percent cover in study areas 2,3,4,5, and 6		
Vegetation Classifications	NDVI 2000	SAVI 2000	TC Greenness 2000
Desert	99	99	100
Highland shrub	1	1	0
Forest	0	0	0
	100.00	100	100.00

In the Southern Highlands (study area 7) the desert vegetation class was similar for the NDVI and SAVI, but the classification of both indices differed from that of the TC Greenness (Tables 3.3 and Figures 3.1, 3.2, and 3.3). Conversely, the classification of the forest area was quite similar for the SAVI and TC Greenness, but both were noticeably different from the classification of the NDVI. The classification of highland shrub areas differed noticeably among the three indices.

Table 3.3 Vegetation Classification (November 25, 1999) for study area 7 (Southern Highlands), where there was a high dominance in the highland shrub class by the NDVI and SAVI, while there was a dominance of desert class by the TC Greenness, and generally, dissimilarity in classification among the indices.

	Percent Change in Vegetation		
Vegetation Classifications	NDVI 1999	SAVI 1999	TC Greenness 1999
Desert	11	11	52
Highland shrub	59	79	41
Forest	30	10	7
	100.00	100.00	100.00

In the Gash Barka (study area 8) the desert vegetation class was similar for the NDVI and SAVI, but the classification of both indices differed from that of the TC Greenness (Tables 3.4 and Figures 3.1, 3.2 and 3.3). Conversely, the classification of the highland shrub area was quite similar for the NDVI and TC Greenness, which were both noticeably different from the SAVI classification. The classification of forest areas differed noticeably among the three indices.

Table 3.4 Vegetation Classification (November 15, 1999) for study area 8 (Gash Barka), where there was a high dominance in the highland shrub class and generally, dissimilarity among the three vegetation indices in the classification method.

	Percent Change in Vegetation		
Vegetation Classifications	NDVI 1999	SAVI 1999	TC Greenness 1999
Desert	19	16	29
Highland shrub	42	66	43
Forest	39	18	28
	100.00	100.00	100.00

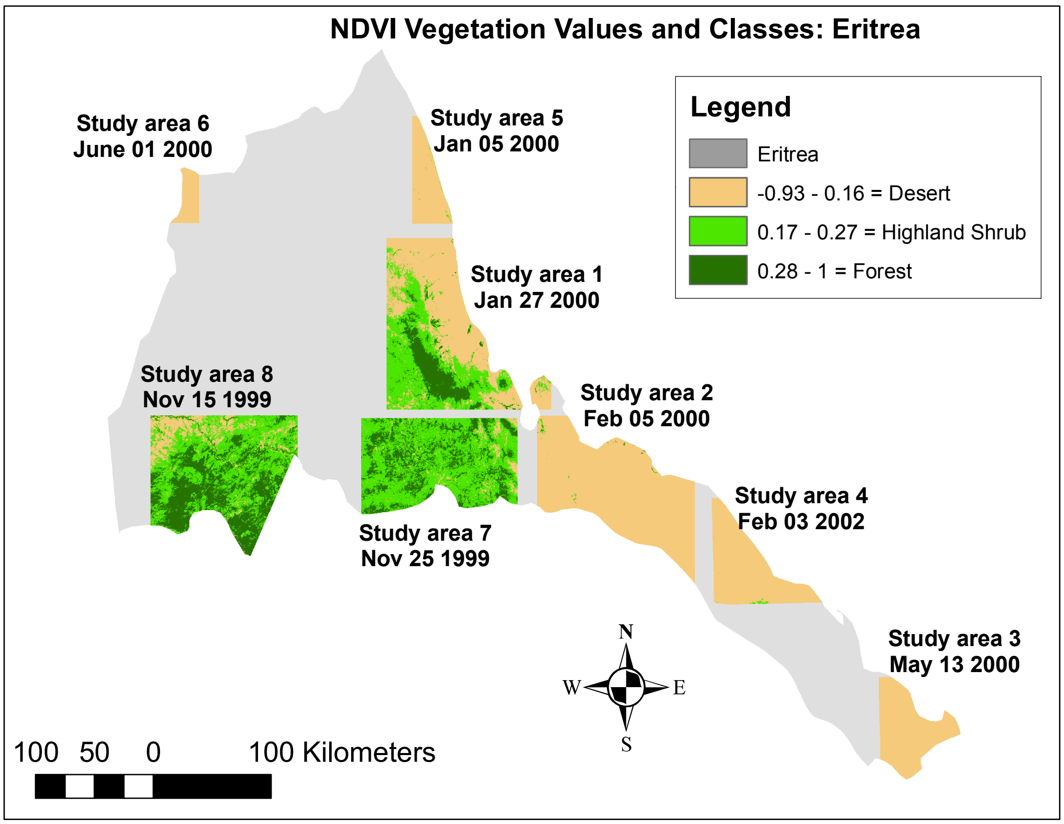

Figure 3.1 NDVI classes during the 1999, 2000, and 2002 periods. Note the high amount of the desert class (yellow color) in all study areas except in study areas 7 and 8, where the dominant NDVI vegetation classes were highland shrub (pale green color) and forest (dark green color) classes.

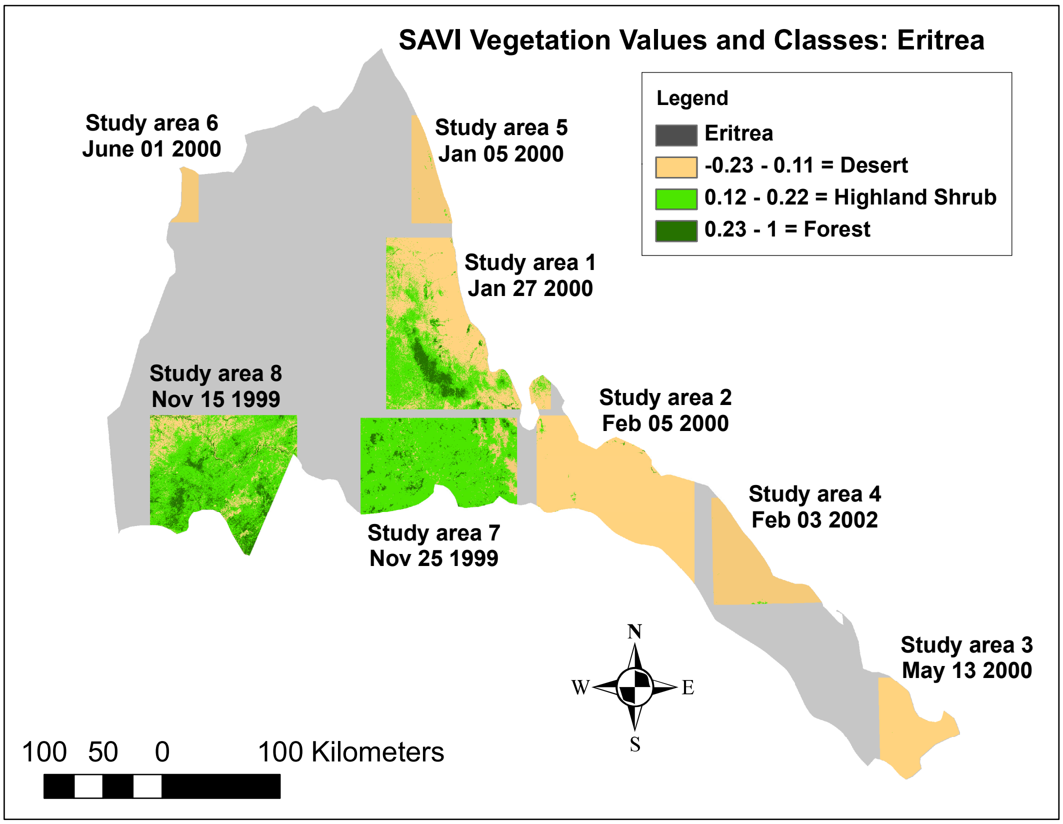

Figure 3.2 SAVI classes during the 1999, 2000, and 2002 periods. Note the high amount of the desert class (yellow color) in all study areas except in study areas 7 and 8, where the dominant NDVI vegetation classes were highland shrub class (dark green).

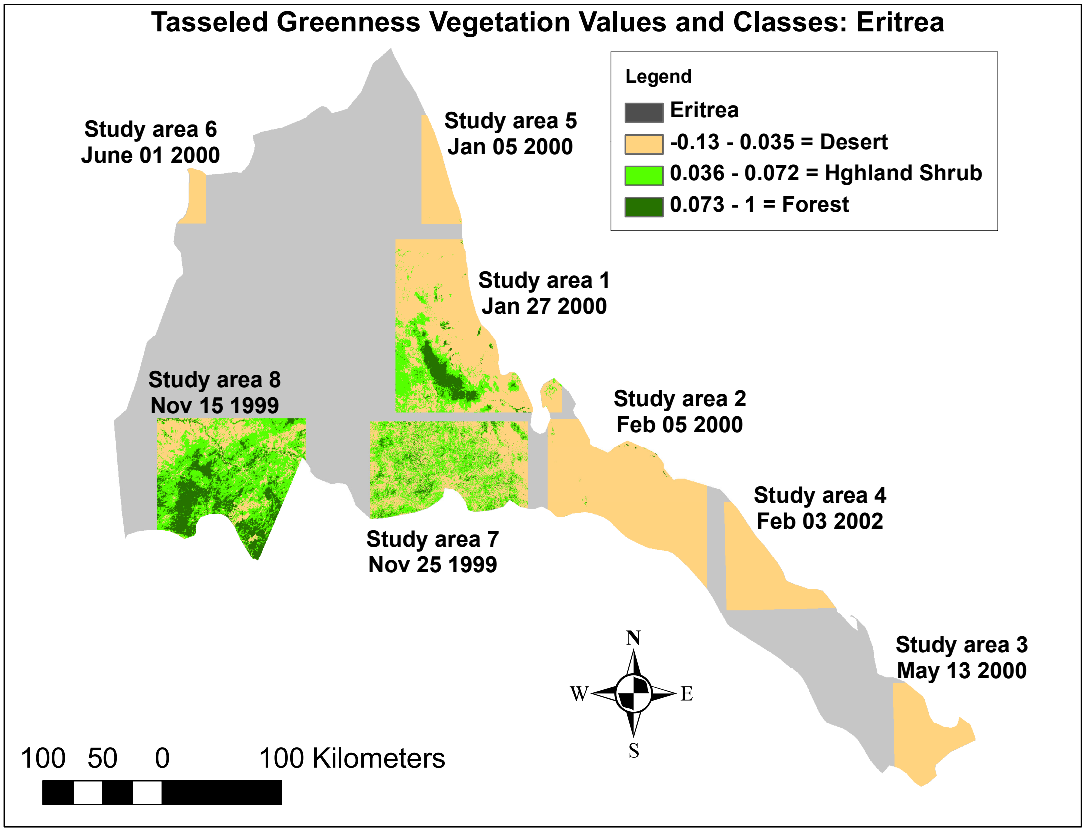

Figure 3.3 TC Greenness Classes during the 1999, 2000, and 2002 periods. Note the almost equal amount of forest, shrub and desert class covers in study areas 7,and 8, while study area 1 showed only a shrub dominance and study areas 2, 3, 4, 5 and 6 show a dominant desert class.

The classification method revealed that Study areas 2, 3, 4, 5, and 6 were deserts while Study areas 1, 7, and 8 comprised of highland shrub, desert and forest areas. There was very high similarity among the three vegetation indices in classifying vegetation classes in study areas 2,3,4,5 and 6 (Table 3.26 and Figures 3.41, 3.42, 3.43). There was a noticeable similarity in classifying the desert class between NDVI and SAVI, and also in the highland shrub class between NDVI and TC Greenness in study area 8 (Table 3.28 and Figures 3.41, 3.42, 3.43).

3.2 Vegetation Change

The detection of changes in vegetation and moisture is important because it is relevant to issues such as species loss, loss of fuel-wood for nomadic cultures, increase in erosion control capacity, monitor agricultural activities, and landscape ecology study. The spatial and temporal patterns of these changes are addressed in this section. Changes in vegetation and moisture were calculated using the NDVI, SAVI, TC Greenness, MSI, and TC Wetness. Change detection results are presented by index, following the order below, for the following eight study areas:

1. Study area 1: Highland, Eastern Escarpment and Coastal Plains.
2. Study area 2: Denkalia (South eastern lowlands zone (coastal plains))
3. Study area 3: South Denkalia (South eastern lowlands zone (coastal plains))
4. Study area 4: Central Denkalia (South eastern lowlands zone (coastal plains))
5. Study area 5: North East Sahel (North eastern lowlands zone (coastal plains))

6. Study area 6: West Sahel (North western lowland)
7. Study area 7: Southern Highlands (Western Escarpment and Central Highland zones)
8. Study area 8: Gash Barka (Mostly on the South Western Lowlands but also on western escarpment zone)

Positive increases in both vegetation and moisture (wetness) levels were shown by the increase in grey color, while the decreases were shown by the increase in the red color in the image displays (Figures 3.4 to 3.43).

3.2.1 Study area 1: Highland, Eastern Escarpment and Coastal Plains

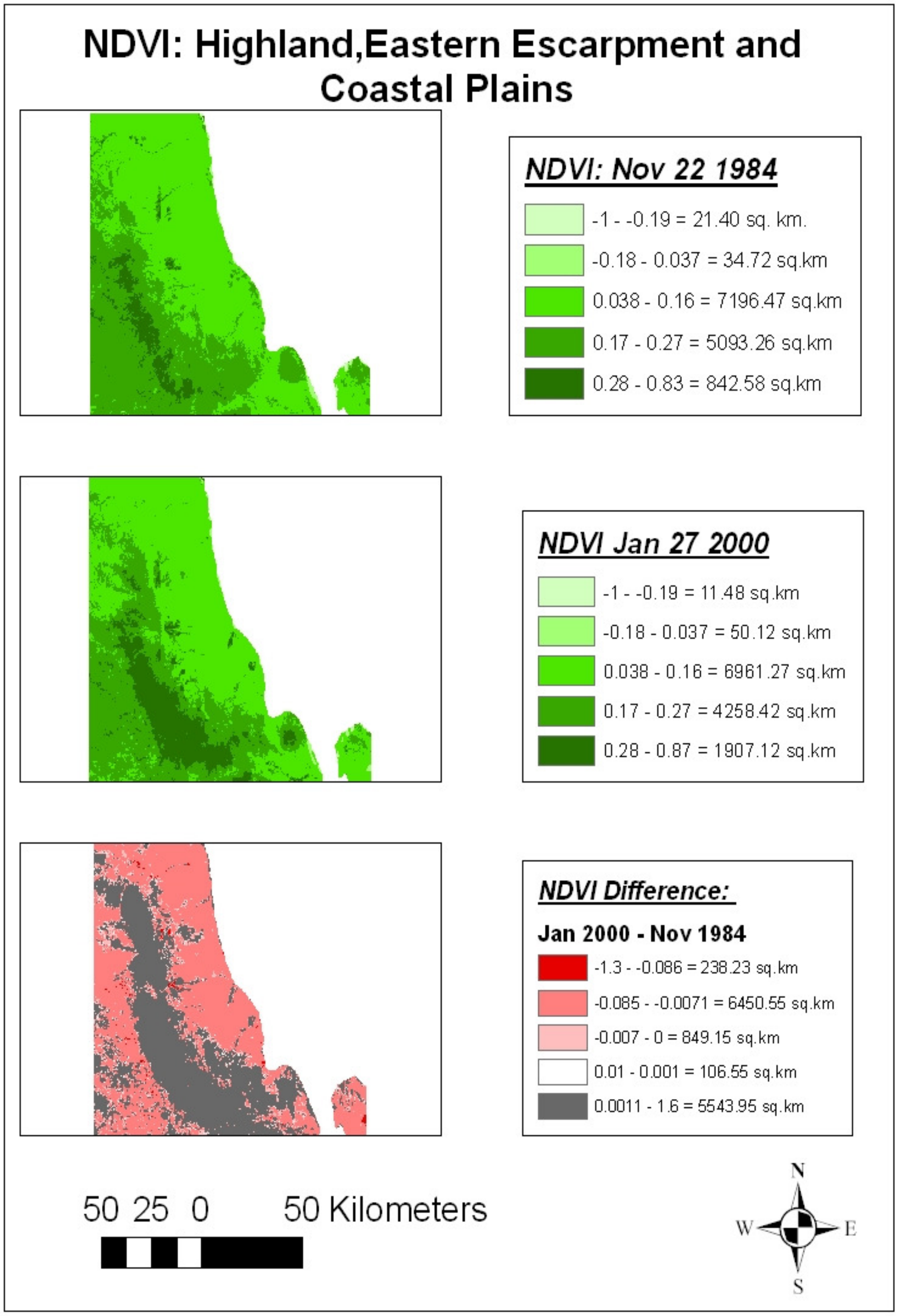

Figure 3.4 NDVI values in Study area 1 (highland, eastern escarpment and coastal plains) showed a decrease (red color) in NDVI vegetation reflectance (57.16%) in the most parts of the coastal plains and central highland areas while showing an increase (gray color) in the Eastern Escarpment (42.04%).

Table 3.5 NDVI percent vegetation reflectance coverage change in Study Area 1 (Highland, Eastern Escarpment, and Coastal Plains). Note the increase in the forest area and the decrease in the highland shrub area which corresponds to the overall decrease in vegetation reflectance

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1984	% of total area in this NDVI range in 2000	%2000 - %1984
Desert ((-1) – 0.16)	55	53	-2
Highland shrub (0.17 - 0.27)	39	32	-7
Forest (0.28 - 1)	6	15	9
	100	100	

In Study area 1, NDVI vegetation reflectance values decreased from 1984 to 2000 in 57% of the study area and increased in 42% (Figure 3.4). However, change did not occur evenly in space, as vegetation increased in the eastern escarpment zone and decreased in the coastal plains and central highland zones (Figure 3.4). Most of the increase was in the forest class as most of the forest was found in the eastern escarpment agro-ecological zone (Table 3.5). The NDVI vegetation reflectance mean values obtained for November 22, 1984 and January 27, 2000 were 0.17 and 0.18, with standard deviations were 0.07 and 0.11, respectively. The coefficients of variability were 0.41 and 0.61, respectively, indicating that the NDVI values from 2000 were more variable than those from 1984.

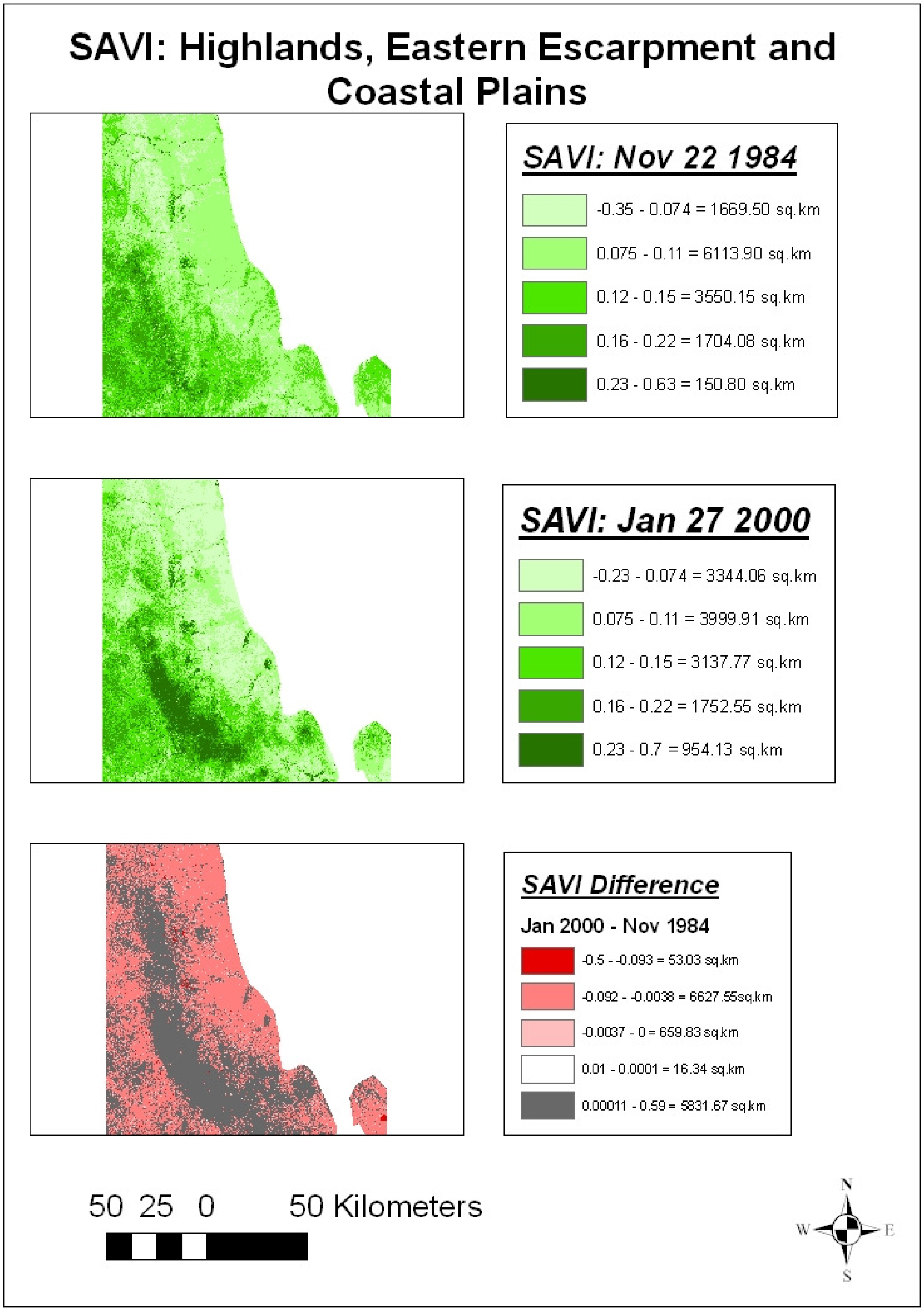

Figure 3.5 SAVI: Study area 1 (Highland Eastern Escarpment and Coastal Plains). Note the similarity with the NDVI value (Figure 3.1) where there is an increase in vegetation reflectance in the eastern escarpment zone and decrease in most parts of the coastal and central highland zones.

Table 3.6 SAVI percent vegetation reflectance cover change in Study Area 1 (the highlands, eastern escarpment, and coastal plains). Note increase in forest area in 2000, and the decrease in the highland shrub and desert areas.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1984	% of total area in this SAVI range in 2000	% 2000 - %1984
Desert ((-1) - 0.11)	59	56	-3
Highland shrub (0.11 - 0.22)	40	37	-3
Forest (0.23 - 1)	1	7	6
Total	100	100	

There was an overall decrease in SAVI vegetation reflectance values in the whole study area from 1984 to 2004. However, as with the NDVI, there was an increase in vegetation in the eastern escarpment (where the forest class is located) and a decrease in the coastal and central highlands (Figure 3.5 and Table 3.6).The mean SAVI values obtained for both November 22, 1984 and January 27, 2000 was 0.07, with standard deviations of 0.06 and 0.08, respectively. The coefficients of variability were 0.86 and 1.14, respectively. Therefore, despite equal mean SAVI values, the 2000 data were more variable than the 1984 data. SAVI vegetation values decreased in 56% of the study area and increased in 44% in 2000 relative to the 1984 levels. These values varied from those of the NDVI (42.04 and 57.16% respectively).

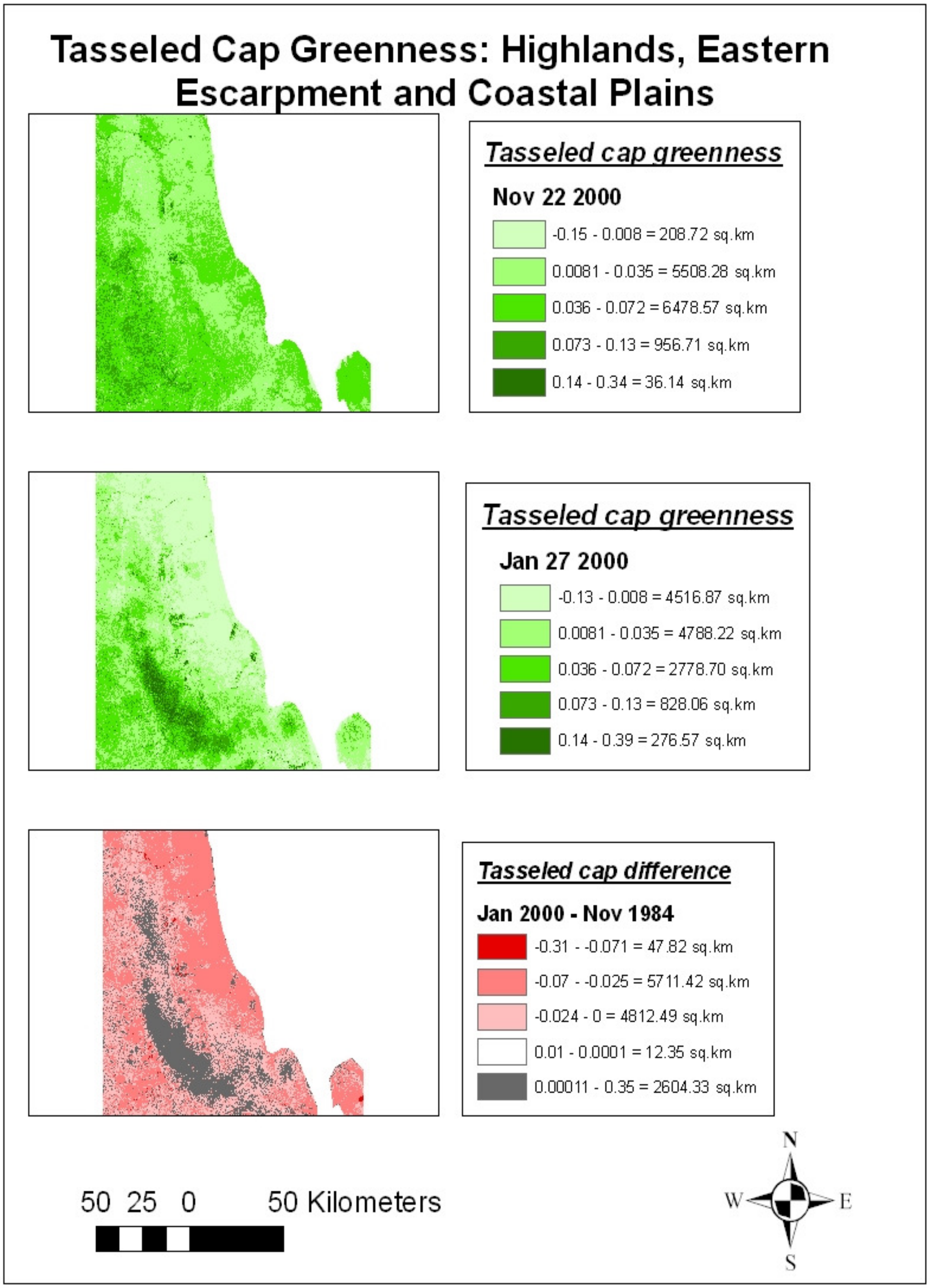

Figure 3.6 TC Greenness: Study area 1 (Highland Eastern Escarpment and Coastal Plains) shows that there was a high amount of vegetation reflectance decrease in 2000 in most of the study area.

Table 3.7 Tasseled Greenness percent vegetation change in Study Area 1 (the highlands, eastern escarpment, and coastal plains). Note the increase in the highland shrub and forest classes (in contrast to the NDVI and SAVI, Table 3.1 and 3.2)

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1984	% of total area in this TC Greenness range in 2000	% 2000 - % 1984
Desert ((-1) - 0.035)	83	71	-12
Highland shrub (0.036 - 0.72)	15	21	6
Forest (0.073 - 1)	2	8	6
	100	100	

The mean TC Greenness values obtained for November 22, 1984 and January 27, 2000, were 0.02 and 0.01, respectively, with equal standard deviations of 0.03. The coefficients of variability were 1.5 and 3, respectively. The January 2000 data were more variable than the November 1984 data. Tasseled Greenness vegetation values decreased in 80% and increased in 20% of the study area from 1984 to 2000 (Figure 3.6). This result is slightly different than those obtained with the SAVI and NDVI, which showed higher decreases in vegetation in roughly half (1/2) of the study area. There was an increase in the highland shrub and forest areas while there was a decrease in the desert area (Table 3.6).

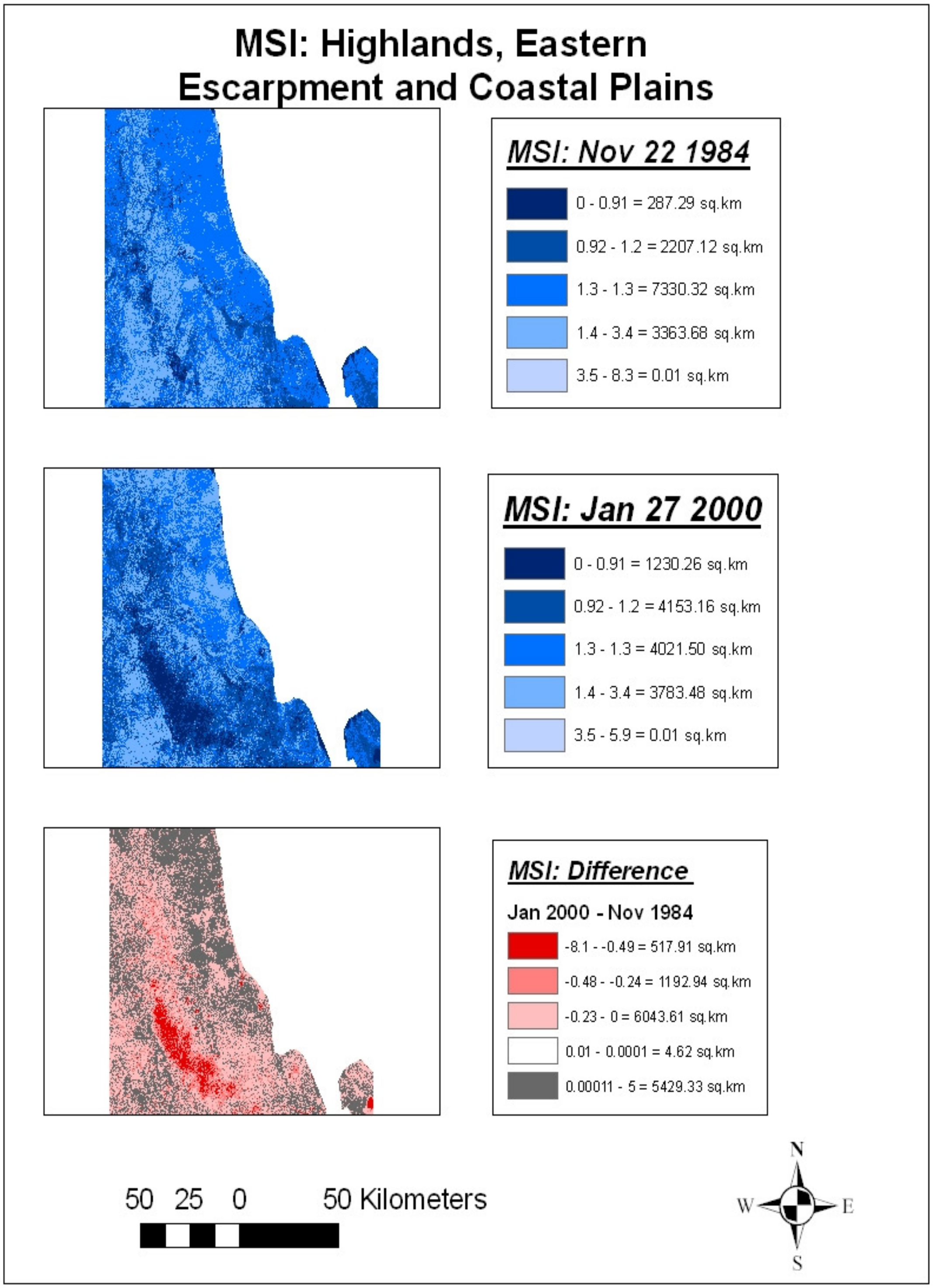

Figure 3.7 MSI: Study area 1 (Highland Eastern Escarpment and Coastal Plains). Note the decrease in moisture stress in the eastern eascarpment (red color) and the decrease in the portions of the highland and coastal plains zone.

The spatial pattern of changes in the MSI corresponds to that of the NDVI, SAVI and TC Greenness, in that MSI values decreased as vegetation cover increased (Figure 3.7). Moisture stress generally decreased in the escarpment area and increased in the coastal zone area. MSI values increased in 41% of the study area in decreased in 59% from 1984 to 2000. Unlike the MSI, the Tasseld Cap Wetness (TC Wetness) analyses showed decreased wetness values in 93% of the study area increased values in 7%from 1984 to 2000 (Figure 3.8). These values contrast with the vegetation changes seen with the NDVI, SAVI, but are more consistent with the TC Greenness.

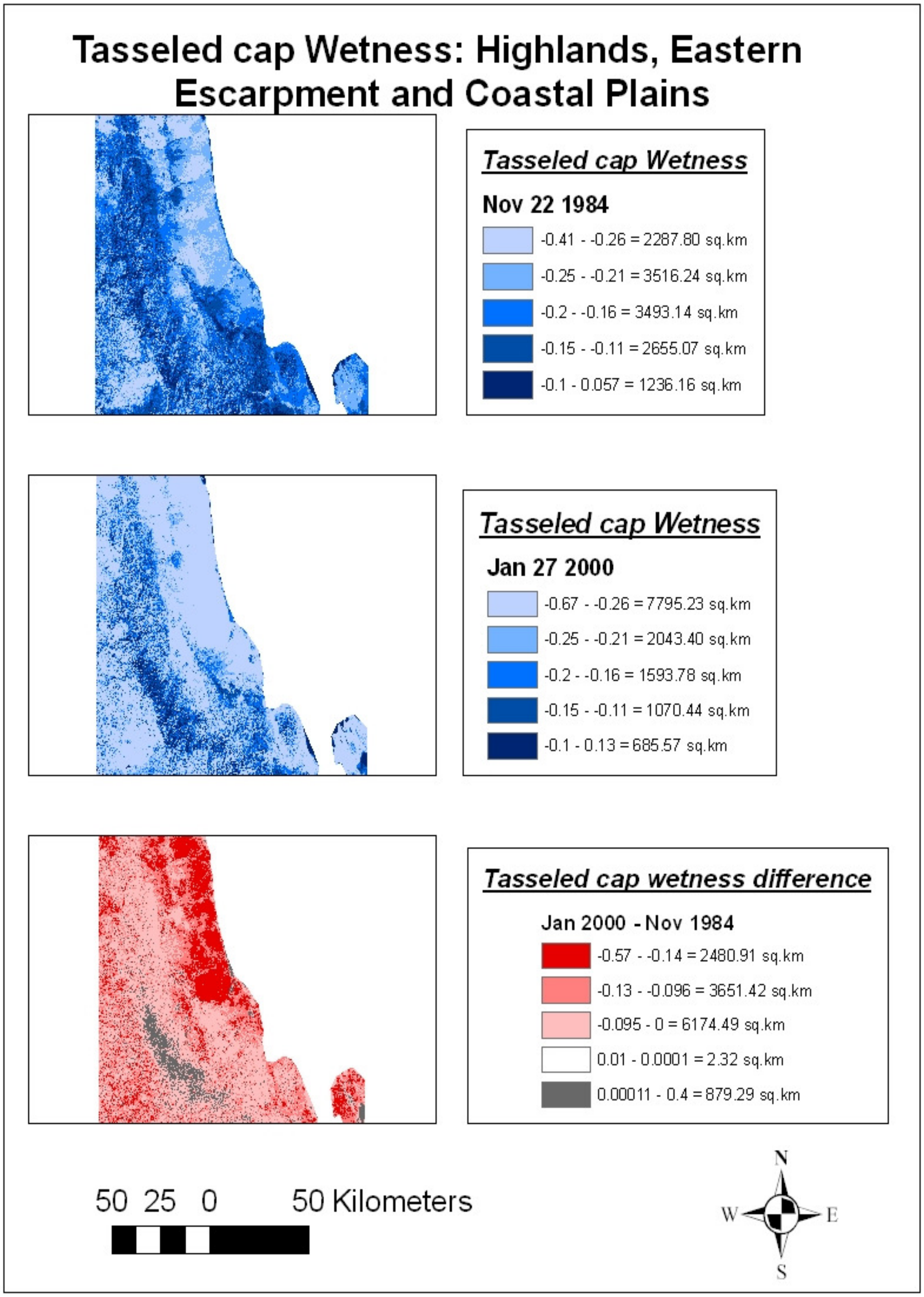

Figure 3.8 TC Wetness analyses: Study area 1 (Highland Eastern Escarpment and Coastal Plains). Note the increase in the TC Wetness value in some portions of the eastern escarpment and the decrease in the central highlands and coastal plains.

3.2.2 *Study area 2: Denkalia*

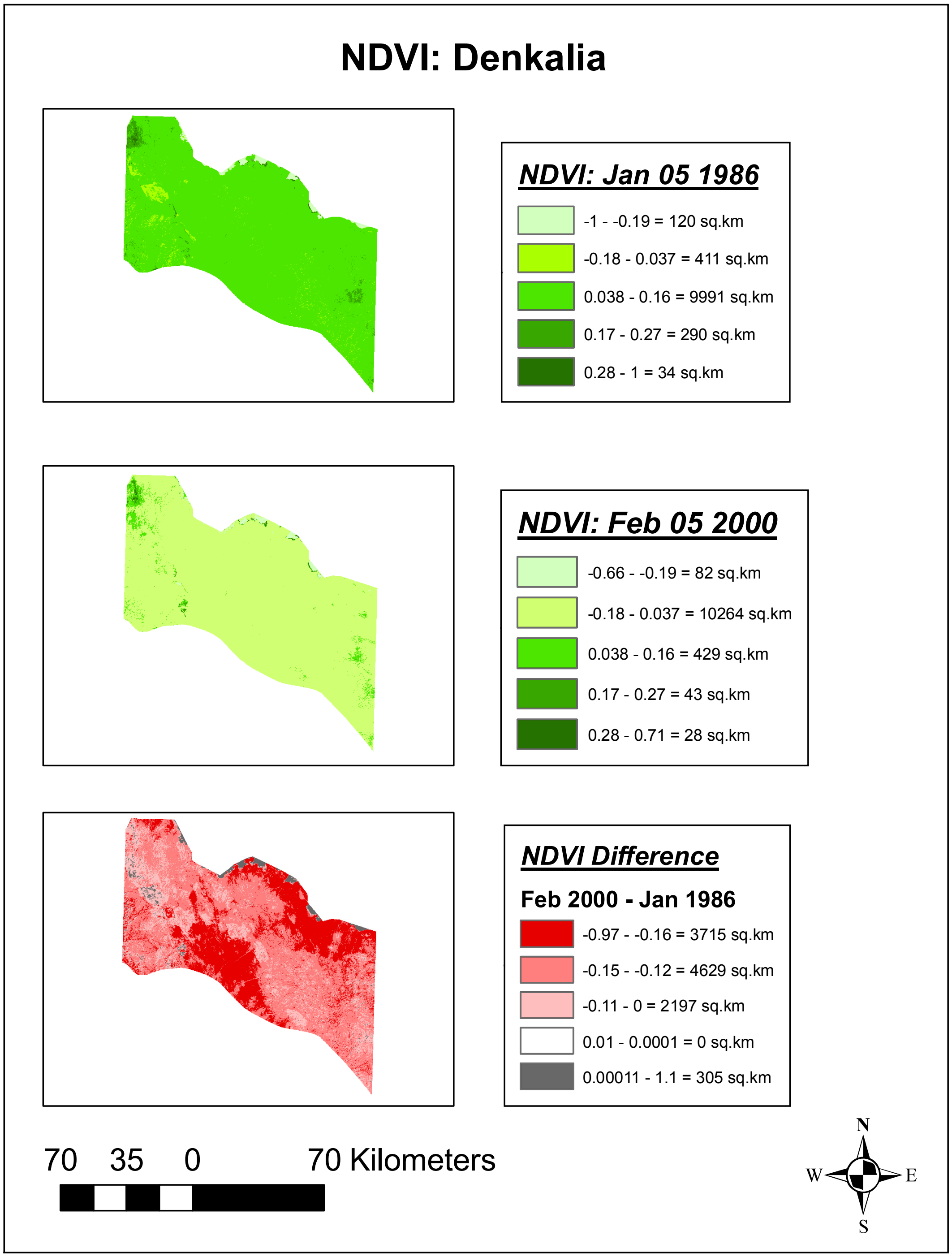

Figure 3.9 NDVI in study area 2: Denkalia (coastal plains zone). There was an overall decrease (the highest being in the central south and northeastern portions) in NDVI vegetation value in all the study area in 2000 from those of 1986, except in the northern tips and some portions in the east.

Table 3.8 NDVI percent vegetation change in study area 2 (Denkalia). Note the increase in the desert area and the decrease in the highland shrub and forest classes.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1986	% of total area in this NDVI range in 2000	% 2000 - % 1986
Desert ((-1) - 0.16)	97	99	2
Highland shrub (0.17 - 0.27)	3	1	-2
Forest (0.28 - 1)	0	0	0
	100	100	

NDVI analysis showed that overall there was a decrease in vegetation with most of the decrease in the south central and northeastern portions of the study area (Figure 3.9). However, visual observation showed that some areas in the northern tip (coast lines) and eastern portions of the study area also showed an increase. The mean NDVI values obtained for January 05 1986 and February 05 2000 were 0.02 and -0.03, respectively. Standard deviations were 0.17 and 0.09, respectively. The coefficients of variability were 8.5 and 3 respectively indicating that the NDVI vegetation values in 1986 were more variable than those from 2000. NDVI vegetation values decreased in 100% and increased in 0% of the study area from 1984 to 2000 (Figure 3.8). The decrease was in the highland shrub and forest classes (Table 3.8).

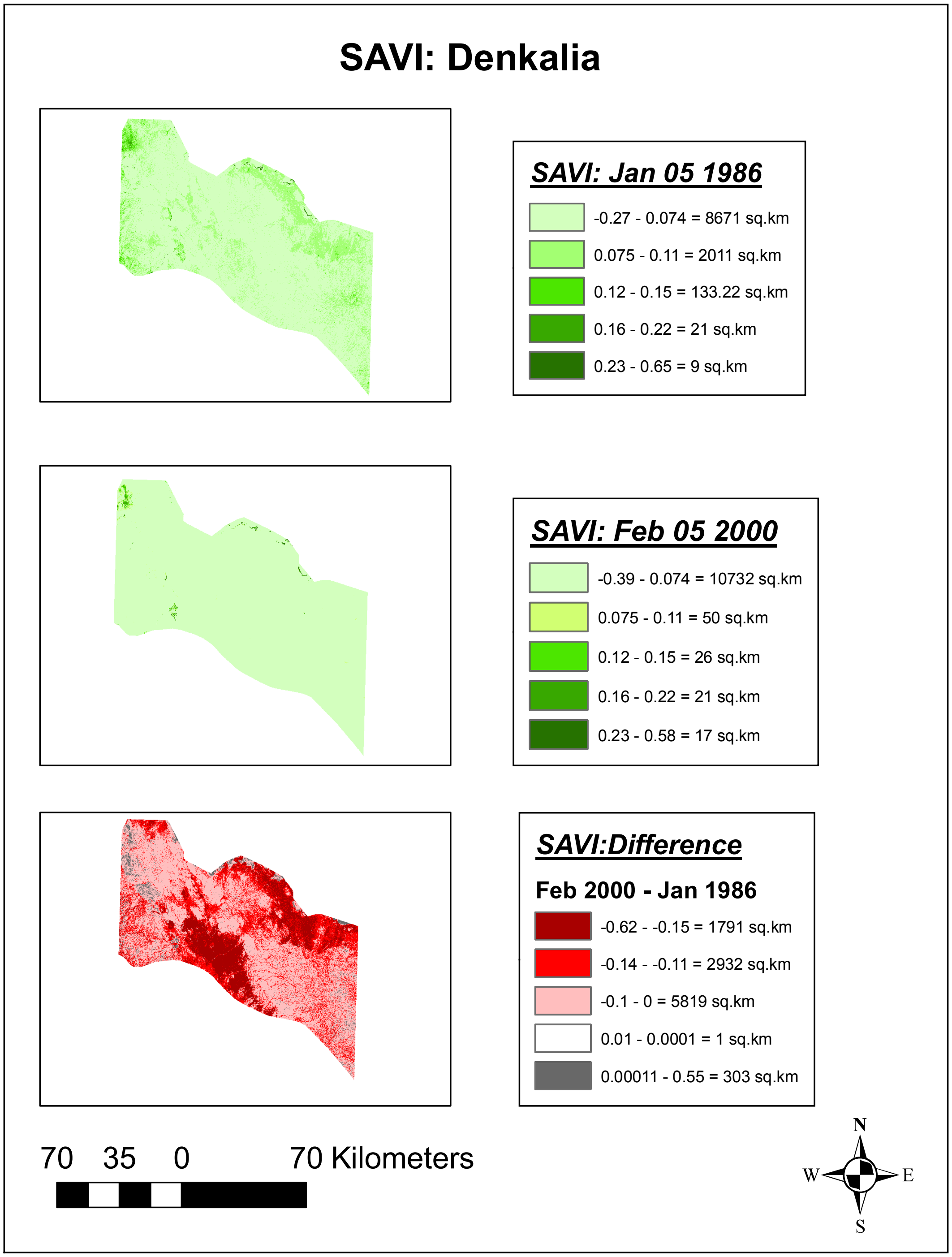

Figure 3.10 SAVI in study area 2: Denkalia (coastal plains zone). There was an overall decrease (the highest being in the central south and northeastern portions) in SAVI vegetation value in all the study area in 2000 from those of 1986, except in the northern tips and some portions in the east.

Table 3.9 : SAVI percent vegetation change in study area 2 (Denkalia). Note the high increase in the desert and forest classes at the expense of the decrease in the highland shrub class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1986	% of total area in this SAVI range in 2000	% 2000 - % 1986
Desert ((-1) - 0.11)	98	99	1
Highland shrub (0.12 - 0.22)	2	1	-1
Forest (0.23 - 1)	0	0	0
Total	100	100	

Similar to the NDVI, the SAVI analysis showed that overall there was a decrease in vegetation with most of the decrease in the south central and northeastern portions of the study area, except for some areas in the northern tip (coast lines) and eastern portions of the study area which showed an increase (Figure 3.10). The mean SAVI values obtained for January 5 1986 and February 5 2000 were 0.04 and -0.03, respectively with equal standard deviation values of 0.05. The coefficients of variability were 1.25 and 1.67 respectively, indicating in contrast to the NDVI, that the SAVI values in 2000 were more variable than those from 1986. SAVI vegetation values decreased in 100% of the study area and increased on 0% from 1984 to 2000 (Figure 3.10). These were very similar to the NDVI except for the forest areas. There was an increase in the desert and forest areas, while there was a decrease in the highland shrub (Table 3.9).

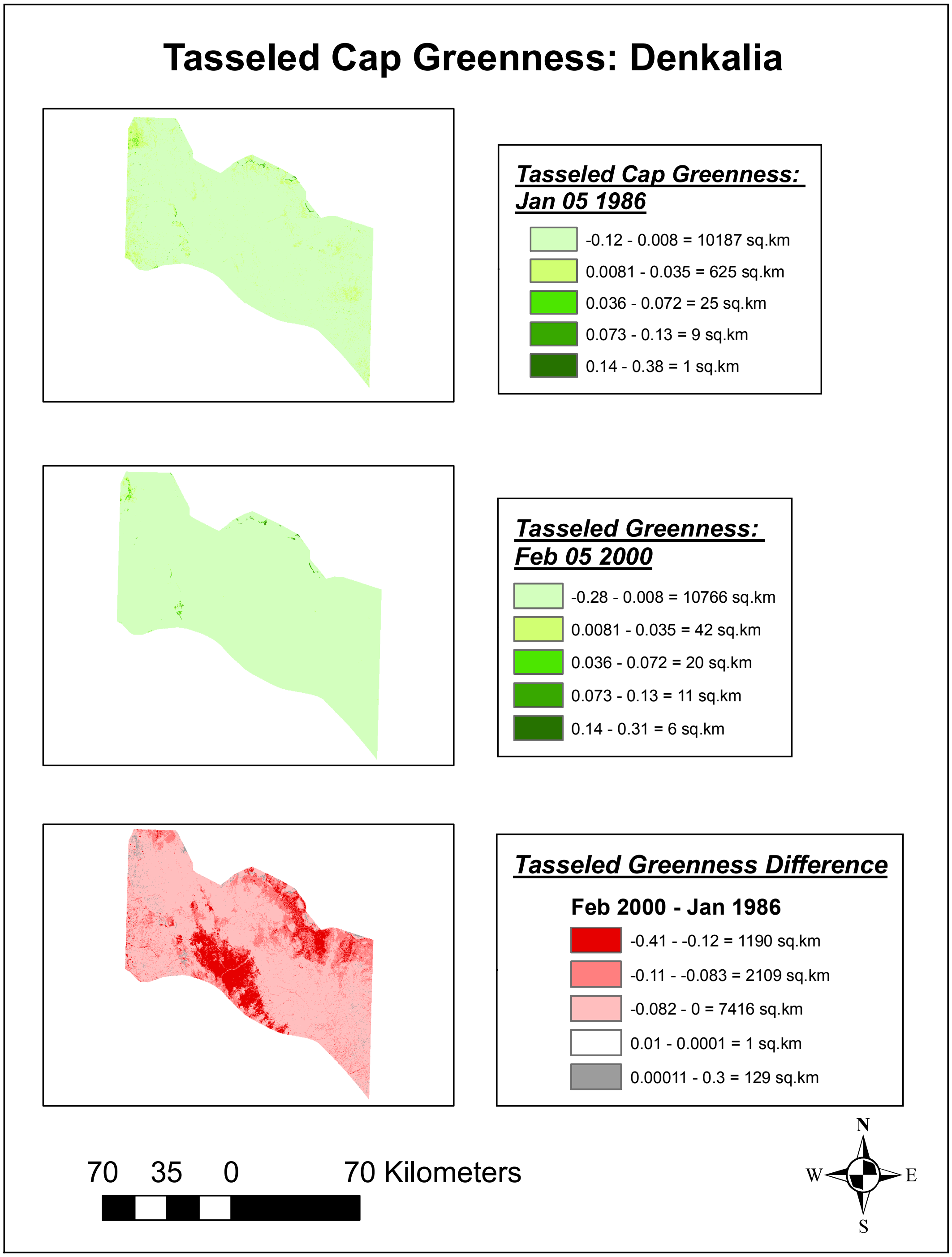

Figure 3.11 TC Greenness analysis in study area 2: Denkalia (coastal plains zone). There was an overall decrease (the highest being in the central south and northeastern portions) in Tasseled Greenness vegetation values in all the study area in 2000 from those of 1986, except in the northern tips and some portions in the east.

Table 3.10 Tasseled Greenness percent vegetation change in study area 2 (Denkalia). Note the decrease in the highland shrub and desert ares and the increase in the forest areas.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1986	% of total area in this TC Greenness range in 2000	% 2000 - % 1986
Desert ((-1) - 0.035)	100	100	0
Highland shrub (0.036 - 0.072)	0	0	0
Forest (0.73 - 1)	0	0	0
	100	100	

The TC Greenness analysis (similar to the NDVI and SAVI) showed that overall there was a decrease in vegetation, with most of the decrease in the south central and northeastern portions of the study area except for some areas in the northern tip (coast lines) and eastern portions of the study area (Figure 3.11). The mean Tasseled Greenness values obtained for January 5 1986 and February 5 2000 were -0.01 and –0.06 respectively. Standard deviation values were 0.01 and 0.04 respectively. The coefficients of variability were 1.00 and 0.67 respectively, indicating like the NDVI that the 1986 values were more variable than those of 2000. Tasseled Greenness vegetation values decreased in 100% and increased in 0% of the study area from 1984 to 2000 (Figure 3.11). These were very similar to the SAVI. There was an increase in the desert and forest areas, and a decrease in highland shrub (Table 3.10).

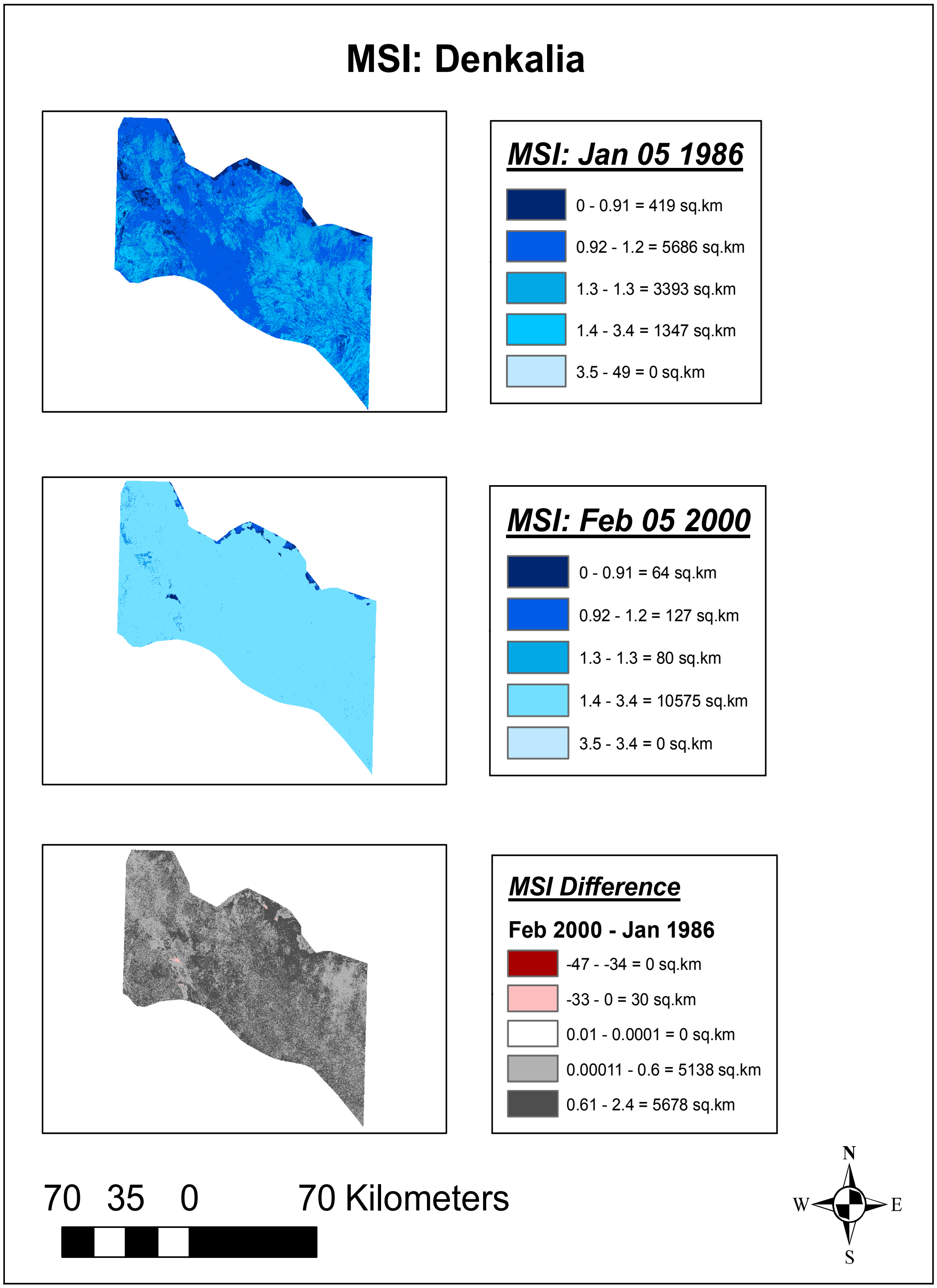

Figure 3.12 MSI: in study area 2: Denkalia (coastal plains zone). There was an overall increase in the MSI value in all the study area in 2000 from that of 1986.

There was a similarity in explaining moisture stress and wetness levels by the MSI and TC Wetness, respectively. MSI values increased in 100% of the study area from 1984 to 2000 (Figure 3.9). The increase corresponded well with the decrease in vegetation as shown in the NDVI, SAVI, and TC Greenness images. Similar to the MSI, the TC Wetness showed a decrease in wetness in 100% of the study area from 1984 to 2000 (Fig 3.10).

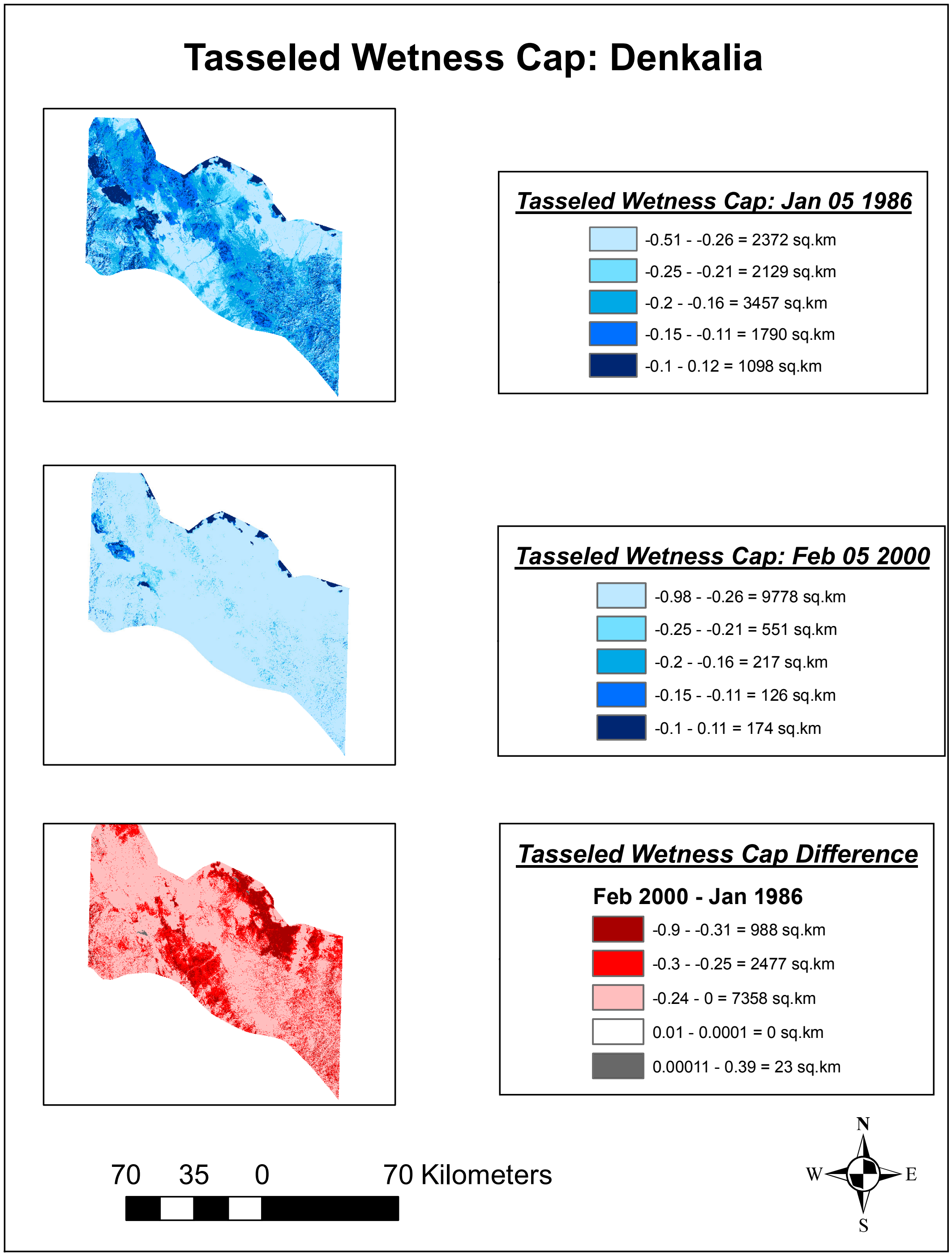

Figure 3.13 TC Wetness: in study area 2: Denkalia (coastal plains zone). There was an overall decrease (the highest being in the central south and northeastern portions) in TC Wetness values in all the study area in 2000 from those of 1986.

3.2.3 *Study area 3: South Denkalia*

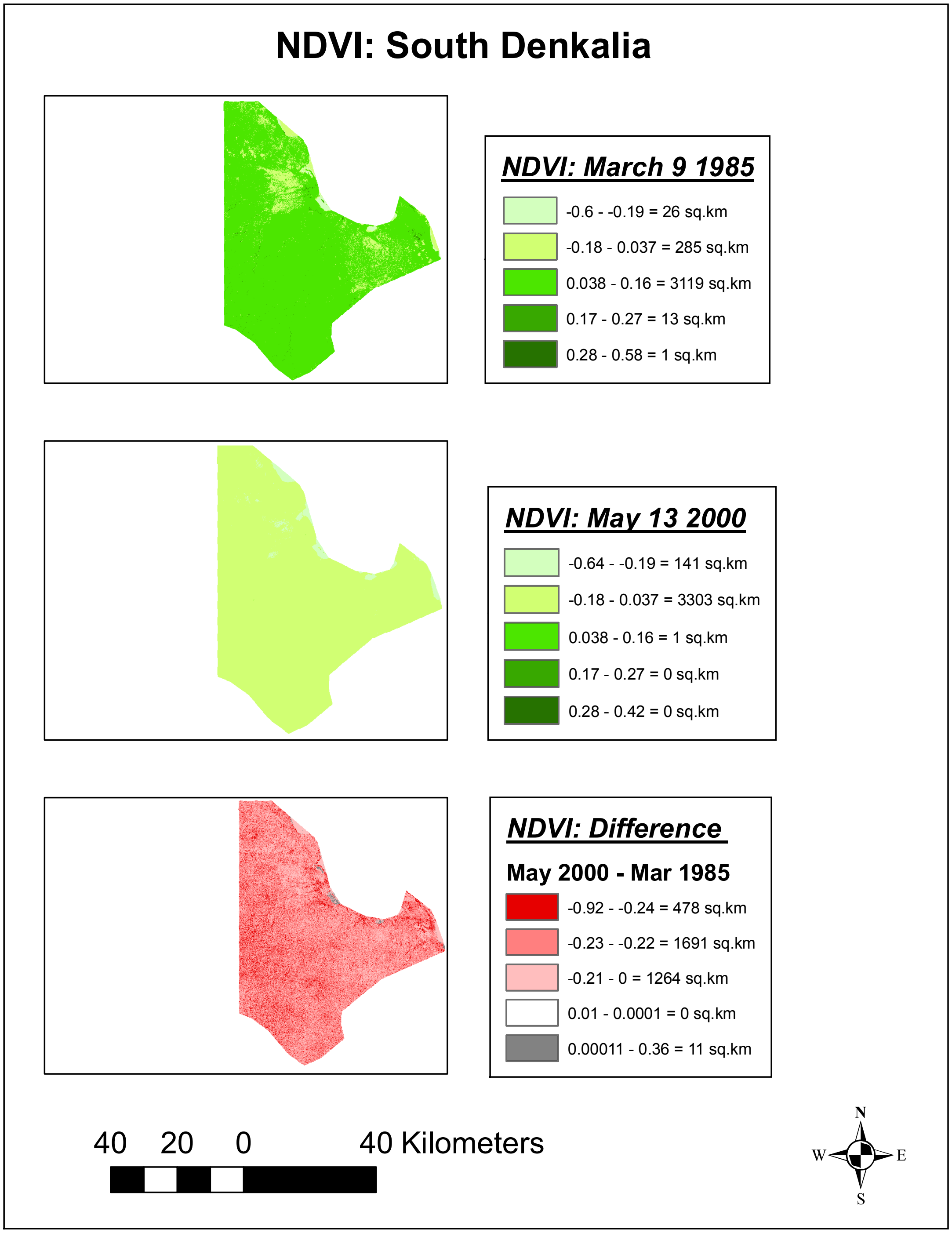

Figure 3.14 NDVI in study area 3: South Denkalia (coastal plains zone). There was an overall decrease in the NDVI value in all the study area in 2000 from those of 1985.

Table 3.11 NDVI percent vegetation change in study area 3 (South Denkalia). Note the decrease in the highland shrub and forest areas and the increase in the desert areas.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1985	% of total area in this NDVI range in 2000	% 2000 - % 1986
Desert ((-1) - 0.16)	100	100	0
Highland shrub (0.17 - 0.27)	0	0	0
Forest (0.28 - 1)	0	0	0
	100	100	

Generally, there was a decrease in the NDVI values in 2000 compared to those of 1985 (Figure 3.14). The mean NDVI values obtained for March 9, 1985, and May 13 2000, were 0.01 and -0.17, respectively. Standard deviations were 0.11 and 0.06, respectively. The coefficients of variability were 11.00 and 0.35 respectively, indicating that the 1985 NDVI values were much more variable than those of 2000. Vegetation decreased in 100% of the study area (Figure 3.13). Vegetation cover classified as highland and shrub and also forest decreased by 100% of their original 1985 amount (Table 3.11).

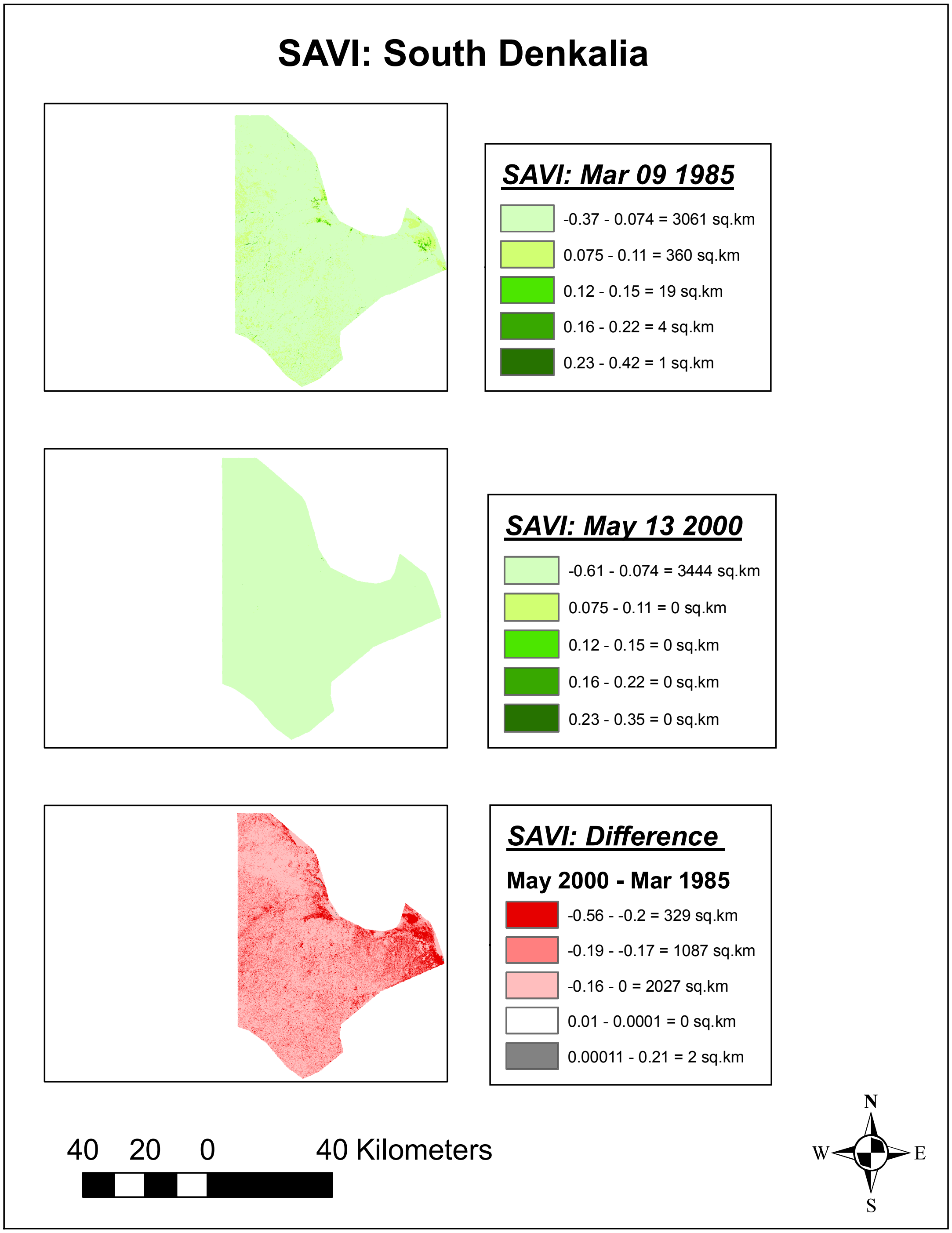

Figure 3.15 SAVI: in study area 3: South Denkalia (coastal plains zone). There was an overall decrease in the SAVI value (similar to the NDVI) in all the study area in 2000 from those of 1985.

Table 3.12 SAVI percent vegetation change in study area 3 (South Denkalia). Note the decrease in the highland shrub and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1985	% of total area in this SAVI range in 2000	% 2000 - % 1985
Desert ((-1) - 0.11)	99	100	1
Highland shrub (0.12 - 0.22)	1	0	-1
Forest (0.23 - 1)	0	0	0
Total	100	100	

Generally, there was a decrease in the SAVI values in 2000 compared to those of 1985 (Figure 3.15).The mean SAVI values obtained for March 9, 1985, and May 13, 2000, were 0.02 and -0.11, respectively. Standard deviations were 0.05 and 0.03 respectively. The coefficients of variability for the two data sets were 2.5 and 0.27, respectively, indicating again as in the NDVI that the 1985 SAVI values were more variable than those of 2000. Vegetation values decreased in 99% of the study area and increased on 0% (Figure 3.15). Almost all the decrease was in the highland shrub class, where the decline was almost 100% of the 1985 level (Table 3.11).

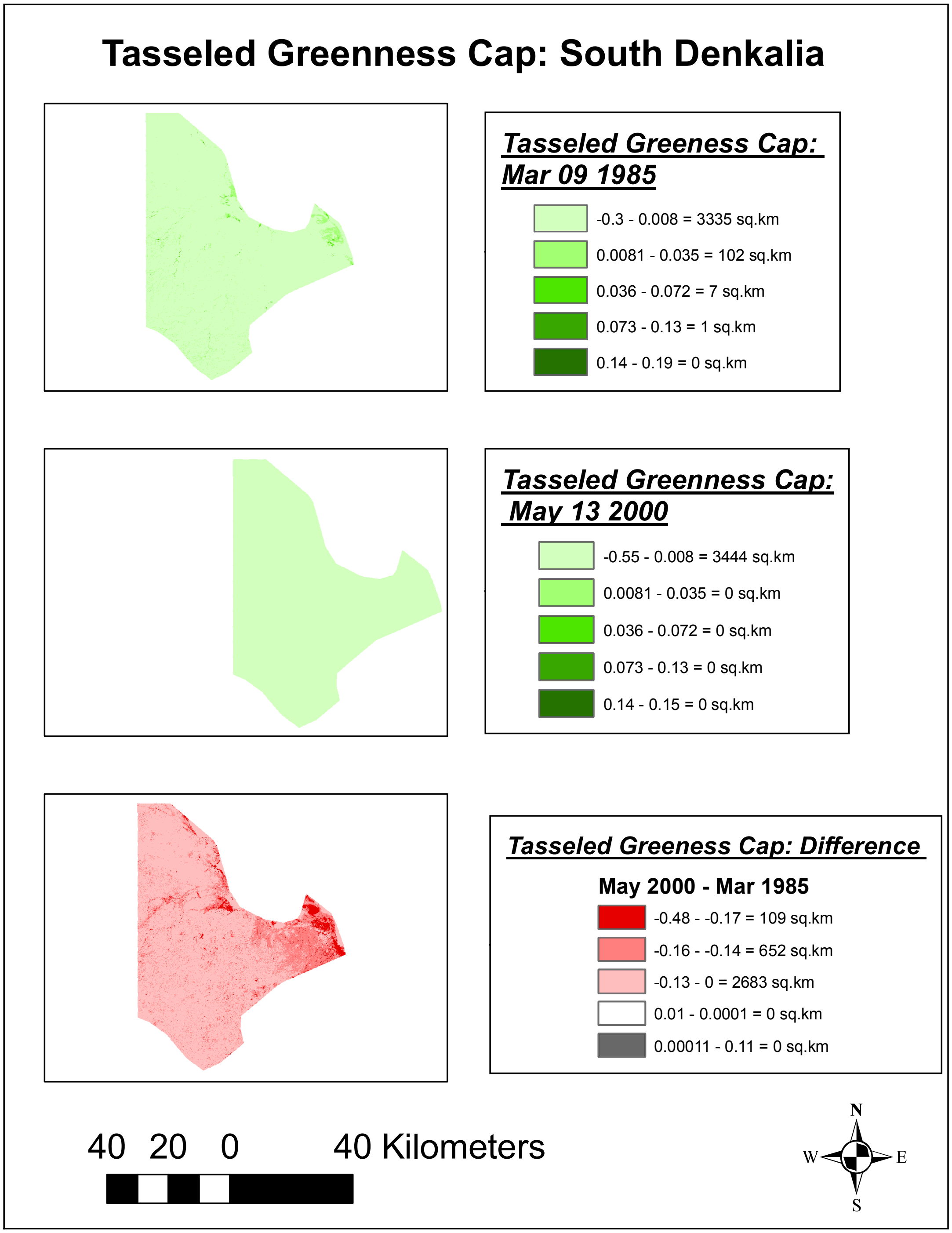

Figure 3.16 Tasseled Greenness in study area 3: South Denkalia (coastal plains zone). There was an overall decrease in the TC Greenness value (similar to the NDVI and SAVI) in all the study area in 2000 from those of 1985.

Table 3.13 Tasseled Greenness percent vegetation change in South Denkalia (Coastal Plains). Note the decrease in the highland shrub and forest classes and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1985	%of total area in this TC Greenness range in 2000	% 2000 - % 1985
Desert ((-1) - 0.035)	100	100	0
Highland shrub (0.036 - 0.072)	0	0	0
Forest (0.073 - 1)	0	0	0
	100	100	

Generally, there was a decrease in the Tasseled Greenness values in 2000 compared to those of 1985 (Figure 3.16).The mean Tasseled Greenness values obtained for May 09, 1985, and May 13, 2000, were -0.01 and –0.13, respectively. Standard deviations were 0.02 and 0.03, respectively. The coefficients of variability were 2.00 and 0.23, respectively, indicating like the NDVI and SAVI that the 1985 Tasseled Greenness values were more variable than those from 2000. Similar to NDVI and SAVI values, according to the TC Greenness, vegetation values decreased on 100% of the study area and increased on 0%. Almost all the decrease was in the highland shrub and forest classes, where the decline was 100% of the 1985 level (Table 3.13).

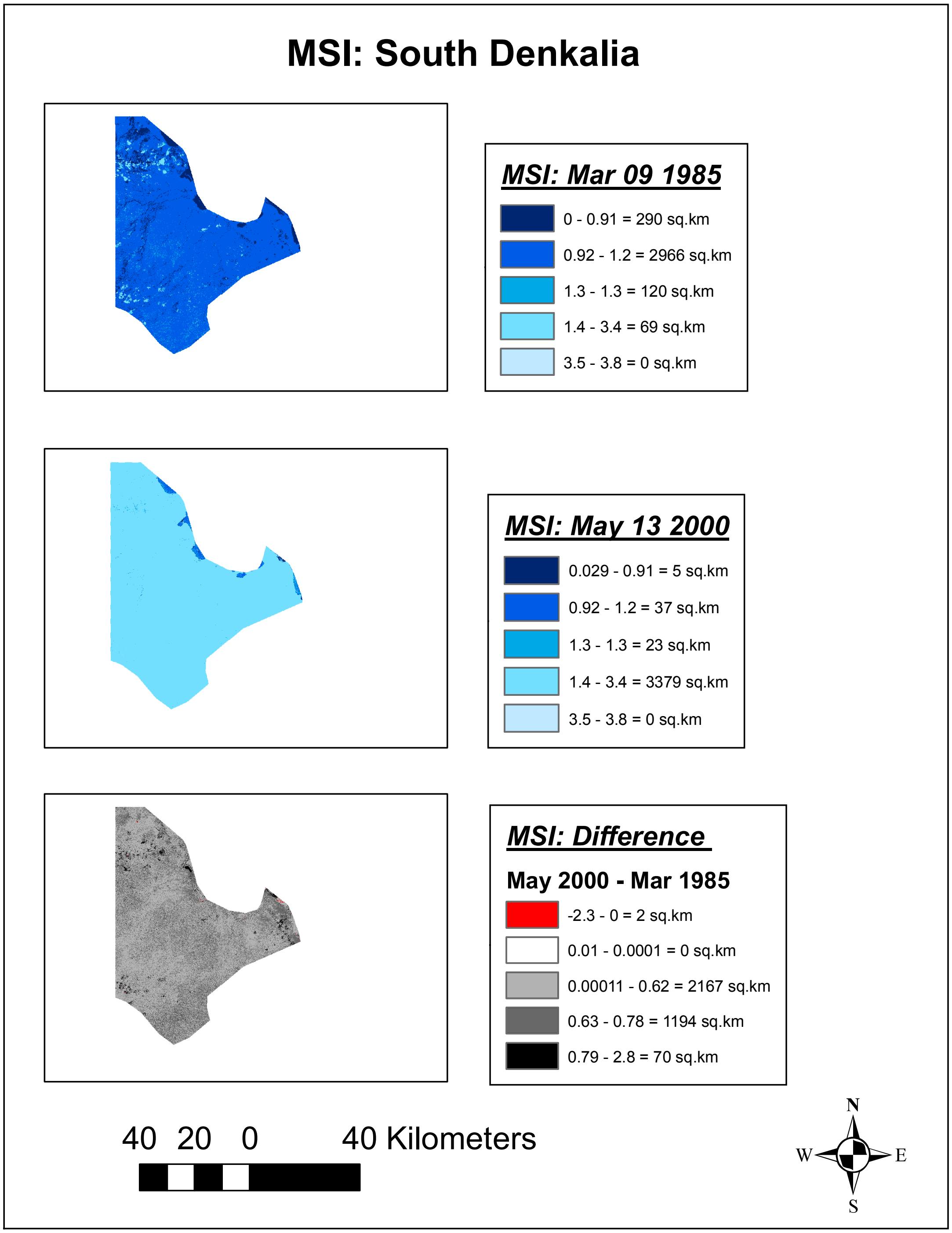

Figure 3.17 MSI analyses in study area 3: South Denkalia (coastal plains zone). There was an overall increase in the MSI value in all the study area in 2000 from those of 1985.

There was a similarity in the results obtained by the MSI and Tasseled Greenness in study area 3. There was an overall increase in MSI on 100% of the study area (Figure 3.17) .The overall increase in moisture stress corresponded with the decrease in vegetation as shown by the NDVI, SAVI, and TC Greenness (Figures 3.14, 3.15 and 3.16). Similarly, there was a decrease in wetness value on 100% of the study area (Fig 3.18). The decrease in wetness corresponds with the decrease in vegetation as shown by the NDVI, SAVI, and TC Greenness (and also increases in moisture stress as shown by MSI).

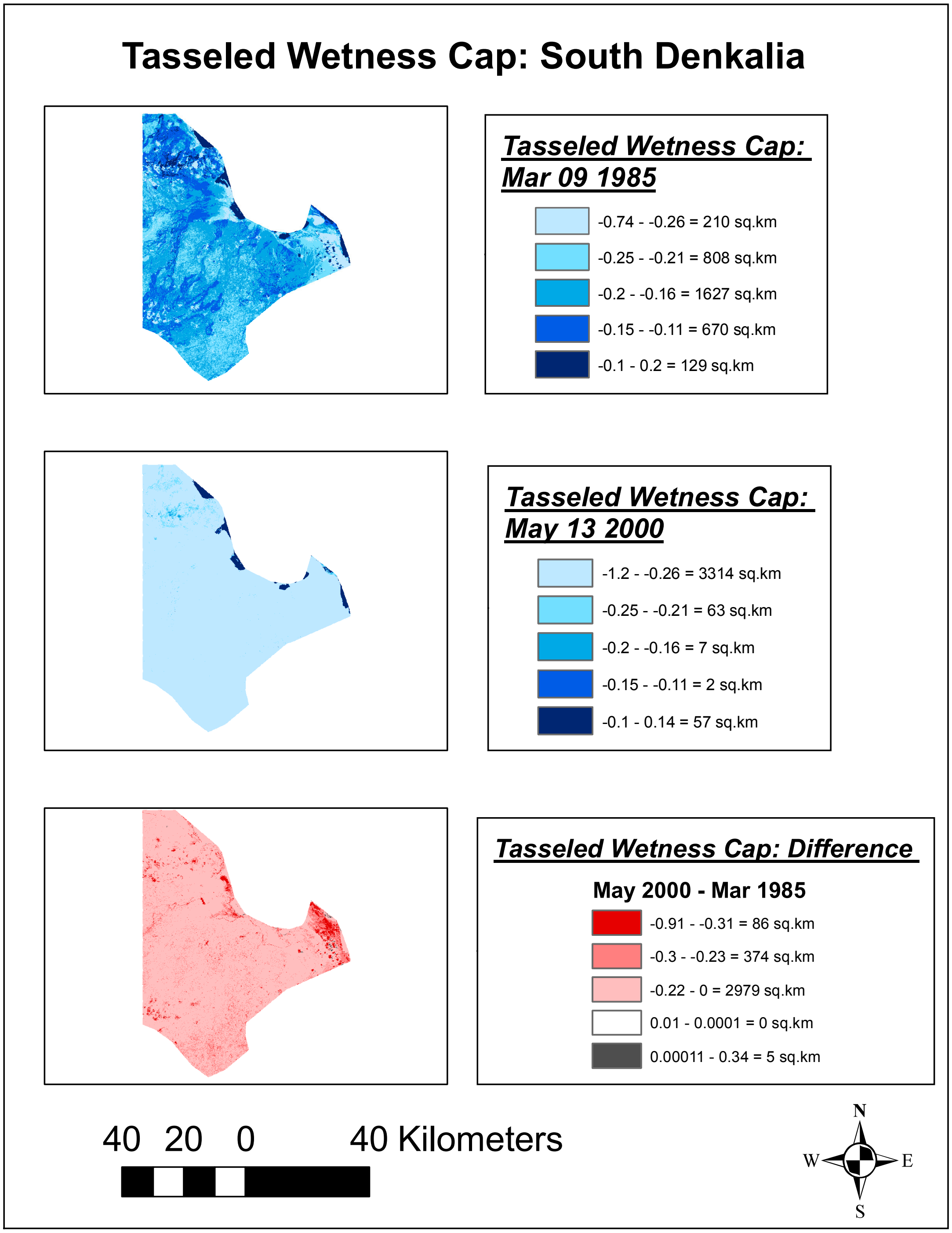

Figure 3.18 TC Wetness in study area 3: South Denkalia (coastal plains zone). There was an overall decrease in the TC Wetness value in all the study area in 2000 from those of 1985.

3.2.4 *Study area 4: Central Denkalia*

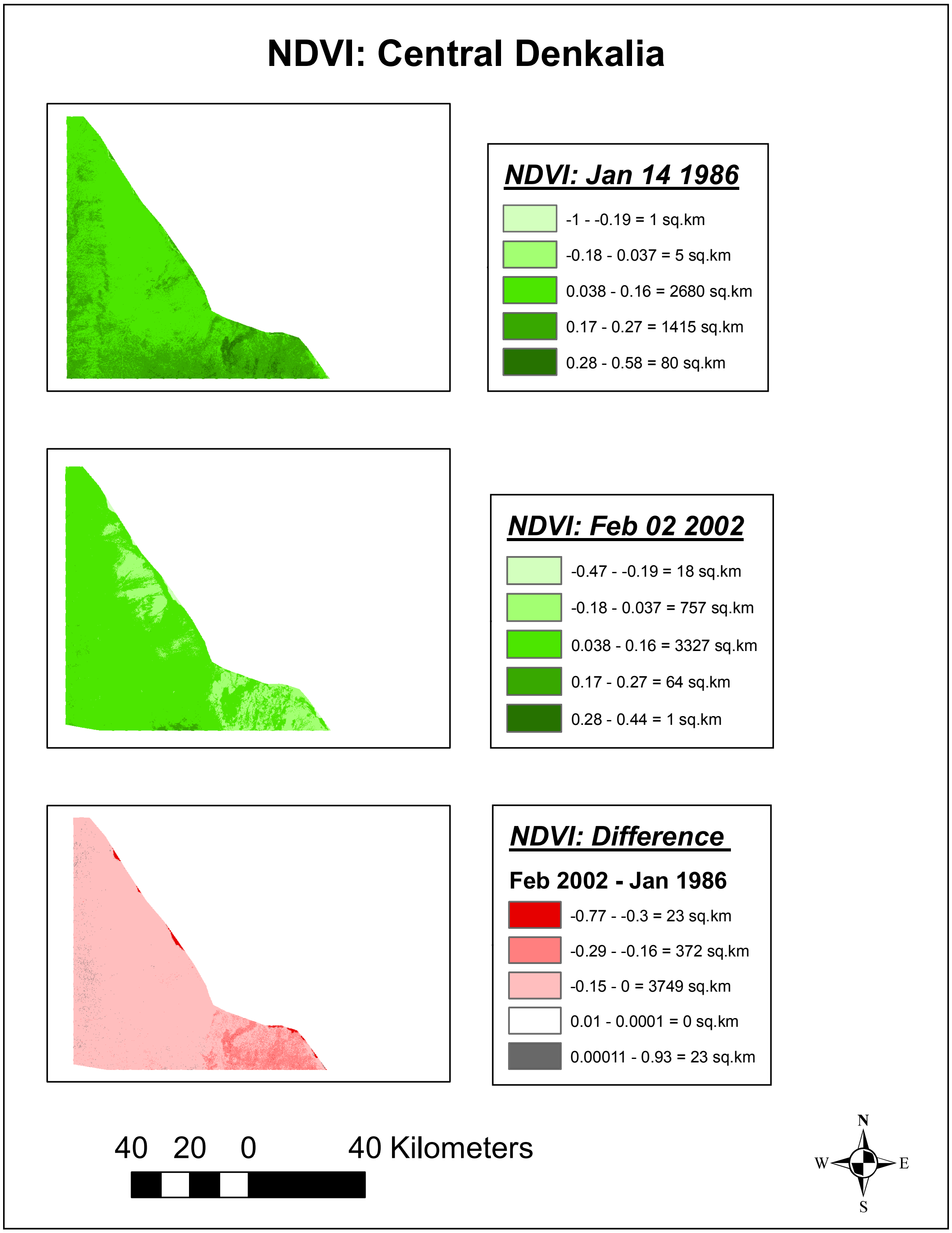

Figure 3.19 NDVI in study area 4: Central Denkalia (coastal plains zone). There was an overall decrease in the NDVI value in all the study area in 2002 from those of 1986.

Table 3.14 NDVI percent vegetation change in study area 4 (Central Denkalia). Note the high decrease in the highland shrub and forest classes and the increase in the desert class

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1986	% of total area in this NDVI range in 2002	% 2002 - % 1986
Desert ((-1) - 0.16)	64	98	34
Highland shrub (0.17 - 0.27)	34	2	-32
Forest (0.28 - 1)	2	0	-2
	100	100	

Generally, there was a decrease in the NDVI values in 2002 compared to those of 1986 with the highest decrease being observed in the southeastern portions and coastal (eastern) tips of the study area (Figure 3.19). The mean NDVI values obtained for January 14, 1986, and February 3, 2002 were 0.24 and -0.01, respectively. Standard deviations were 0.09 and 0.07, respectively. The coefficients of variability were 0.38 and 7.00, respectively, indicating that the 2002 NDVI values were more variable than those from the 1986. NDVI vegetation values decreased in 99% of the study area and increased on 1%. Both the highland shrub and the forest classes decreased and the desert class increased (Table 3.14).

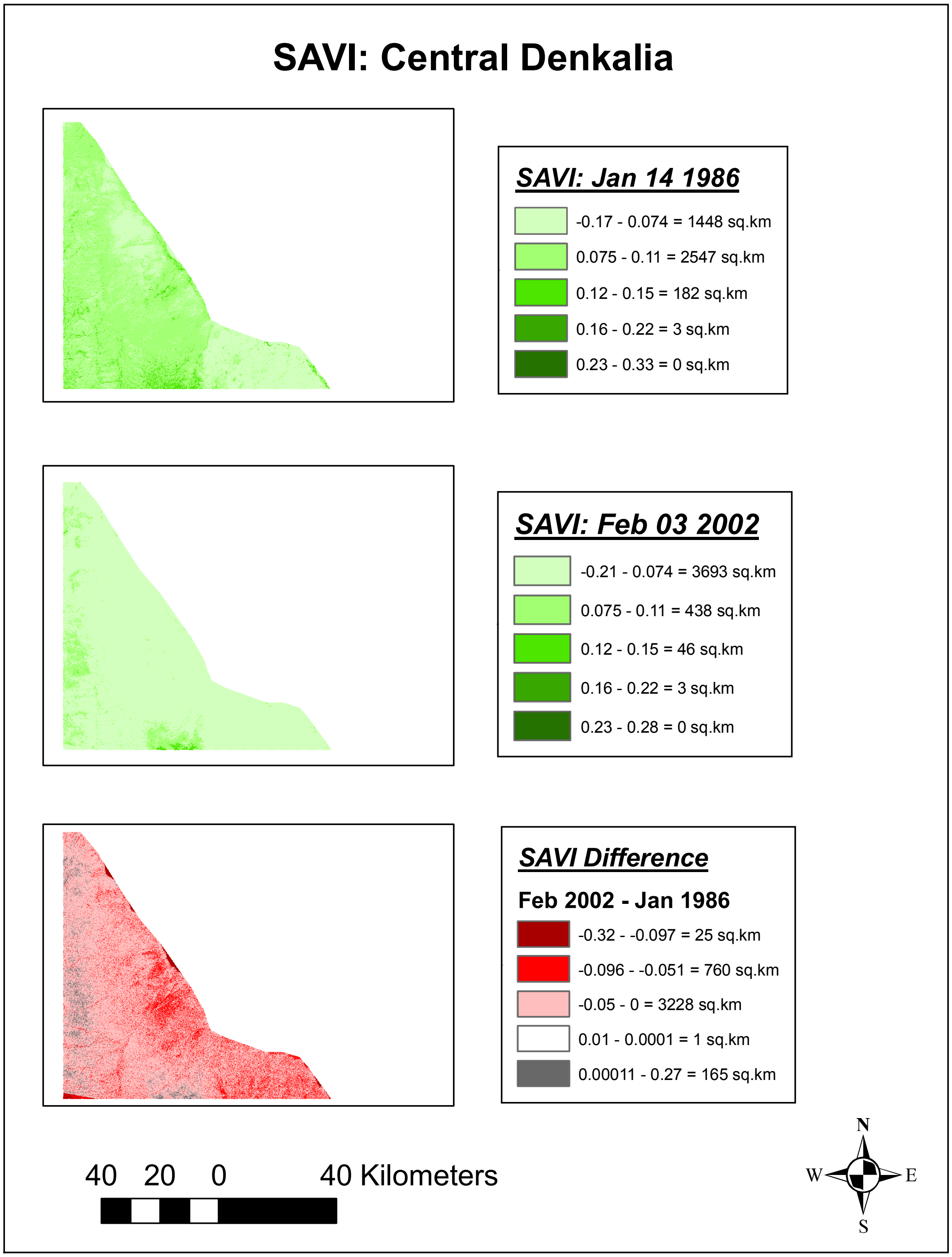

Figure 3.20 SAVI in study area 4: Central Denkalia (coastal plains zone). There was an overall decrease in the SAVI value in all the study area in 2002 from those of 1986 except for some areas in the southern portions of the study area.

Table 3.15 SAVI percent vegetation change in study area 4 (Central Denkalia). Note the decrease in the highland shrub class and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1986	% of total area in this SAVI range in 2002	% 2002 - % 1986
Desert ((-1) - 0.11)	96	99	3
Highland shrub (0.12 - 0.22)	4	1	-3
Forest (0.23 - 1)	0	0	0
Total	100	100	

Similar to the NDVI, there was a decrease in the SAVI values in 2002 compared to those of 1986 with the highest decrease being observed in the southeastern portions and coastal (eastern) tips of the study area. The mean SAVI values obtained for January 14, 1986, and February 3, 2002, were 0.05 and 0.01, respectively, with equal standard deviations of 0.03. The coefficients of variability were 0.6 and 3, respectively, indicating that the 2002 SAVI vegetation values were more variable in space than those from 1986. SAVI vegetation values increased on 96% of the study area and decreased on 4% and unlike the NDVI values, the SAVI method showed an increase in vegetation in some parts of the southern portion of the image depicted by grayish color (Figure 3.20). All of the decrease (100% decrease relative to the

1986 levels) was felt by the highland shrub class leading to the increase in the desert class (Table 3.15).

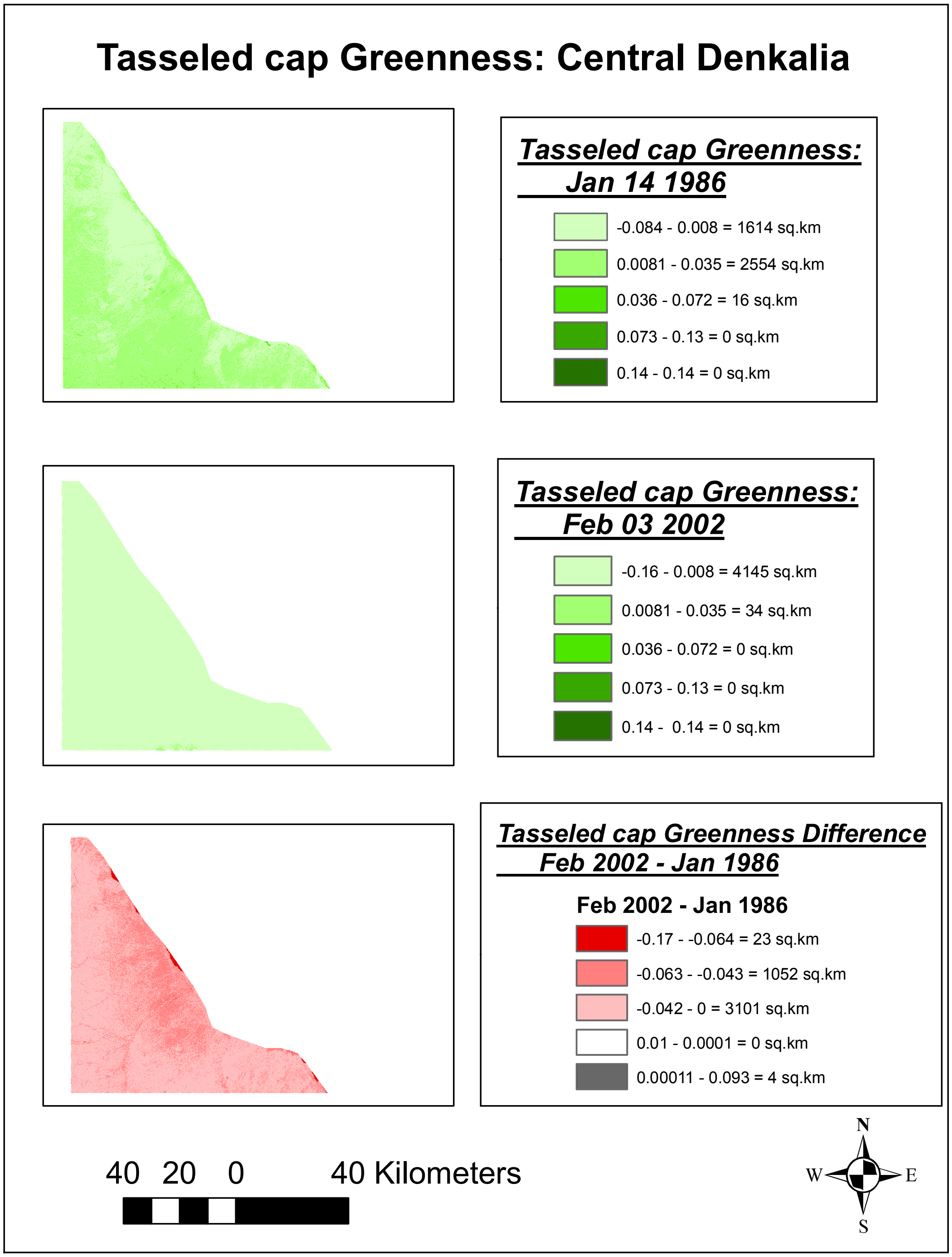

Figure 3.21 Tasseled Greenness in study area 4: Central Denkalia (coastal plains zone). There was an overall decrease in the Tasseled Greenness value in all the study area in 2002 from those of 1986.

Table 3.16 Tasseled Greenness percent vegetation change in study area 4 (Central Denkalia). Note that all the study area is classed as desert in both time data sets with no change.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1986	% of total area in this TC Greenness in 2002	% 2002 - % 1986
Desert ((-1) - 0.035)	100.00	100.00	0.00
Highland shrub (0.036 - 0.072)	0.00	0.00	0.00
Forest (0.073 - 1)	0.00	0.00	0.00
	100	100	

Similar to the NDVI and SAVI, there was a decrease in the Tasseled Greenness values in study area 4 (Figure 3.21). The mean Tasseled Greenness values obtained for January 14, 1986, and February 03, 2002, were 0.01 and -0.03, respectively, with equal standard deviations of 0.01. The coefficients of variability were 1.00 and 0.33, respectively, indicating unlike the NDVI and SAVI that the 1986 Tasseled Greenness vegetation values were more variable in space than those from 2000.TC Greenness vegetation values decreased on 100% of the study area and increased on 0% (Figure 3.20). The Tasseled Greenness increase and decrease patterns in the vegetation values in study area 4 were similar to those obtained from NDVI but not from SAVI. Unlike the NDVI and SAVI assessments, all the study area was classed as desert in both time-datasets with no change (Table 3.16).

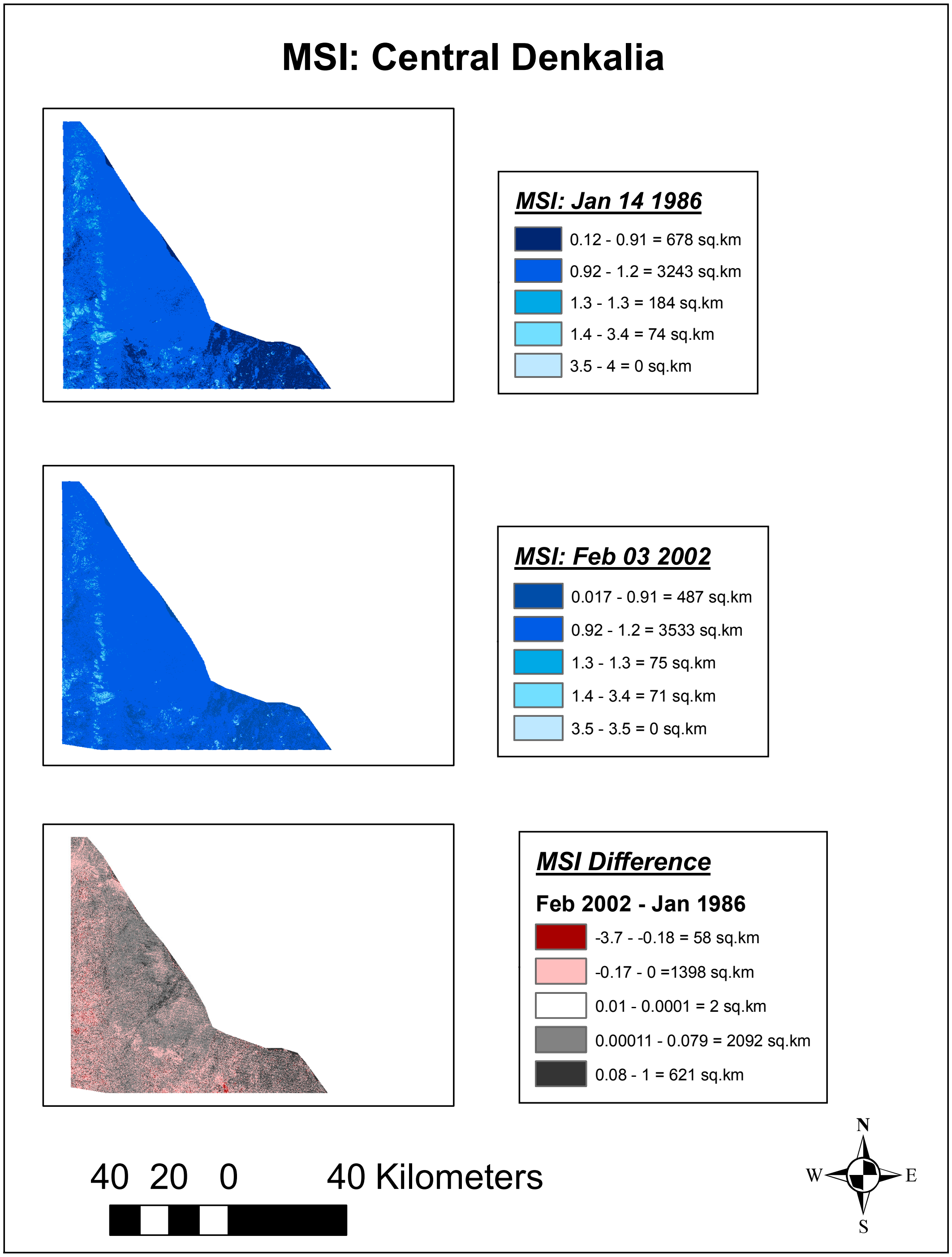

Figure 3.22 MSI Analysis in study area 4: Central Denkalia (coastal plains zone). There was an overall a higher increase than decrease in the MSI value in all the study area in 2002 from those of 1986.

There was a similarity in the results obtained by the MSI and Tasseled Greenness in study area 4. There was an overall increase in MSI on 65% of the study area (Figure 3.19) .The overall increase in moisture stress corresponded with the decrease in vegetation as shown by the NDVI, SAVI, and TC Greenness. Similarly, there was a decrease in wetness value on 98% of the study area (Fig 3.20). The decrease in wetness corresponds with the decrease in vegetation as shown by the NDVI, SAVI, and TC Greenness (and also increases in moisture stress as shown by MSI).

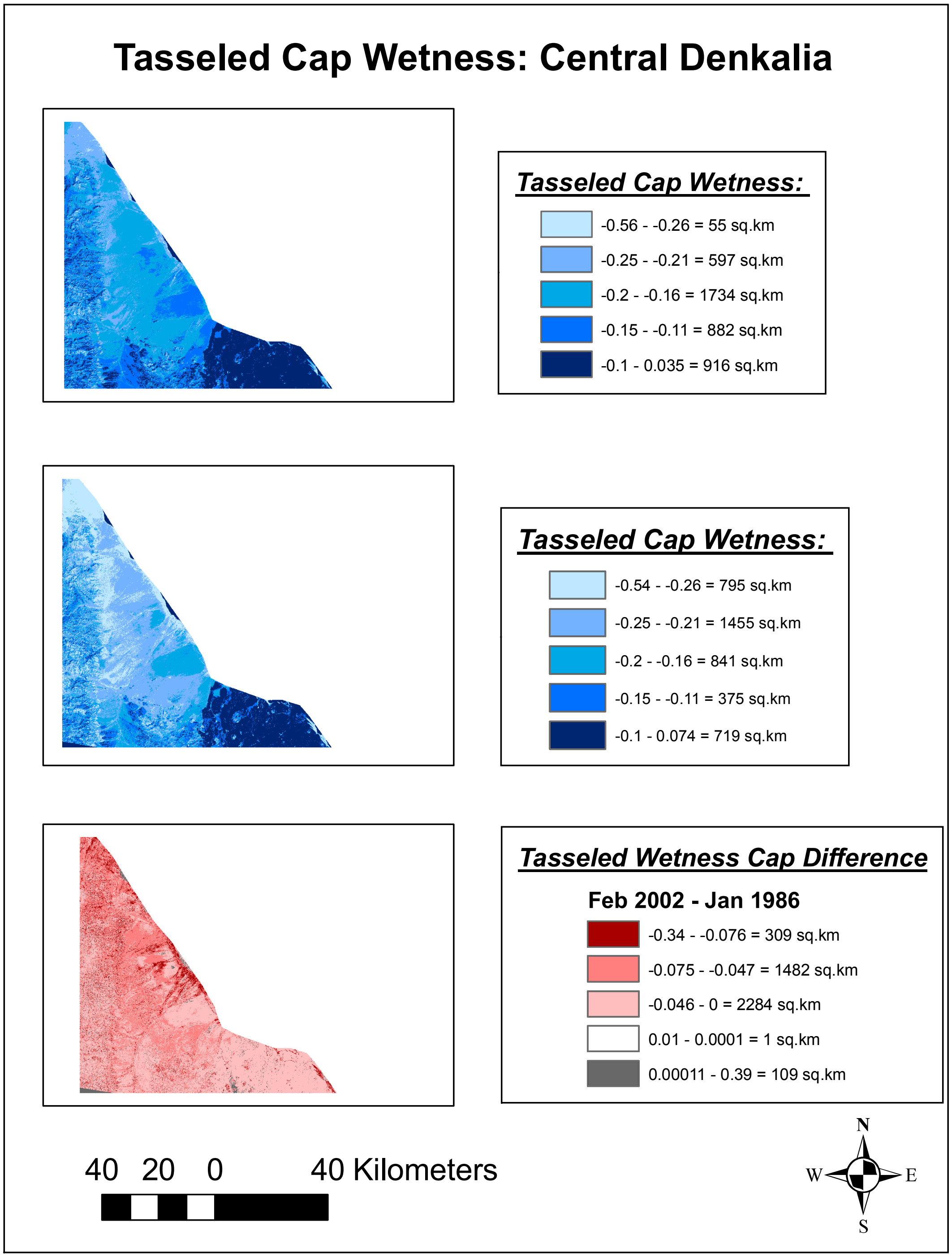

Figure 3.23 TC Wetness analyses in study area 4: Central Denkalia (coastal plains zone). There was an overall decrease in the TC Wetness value in 2002 from those of 1986 except for some areas in the southern tip portions of the study area.

3.2.5 Study area 5: North East Sahel

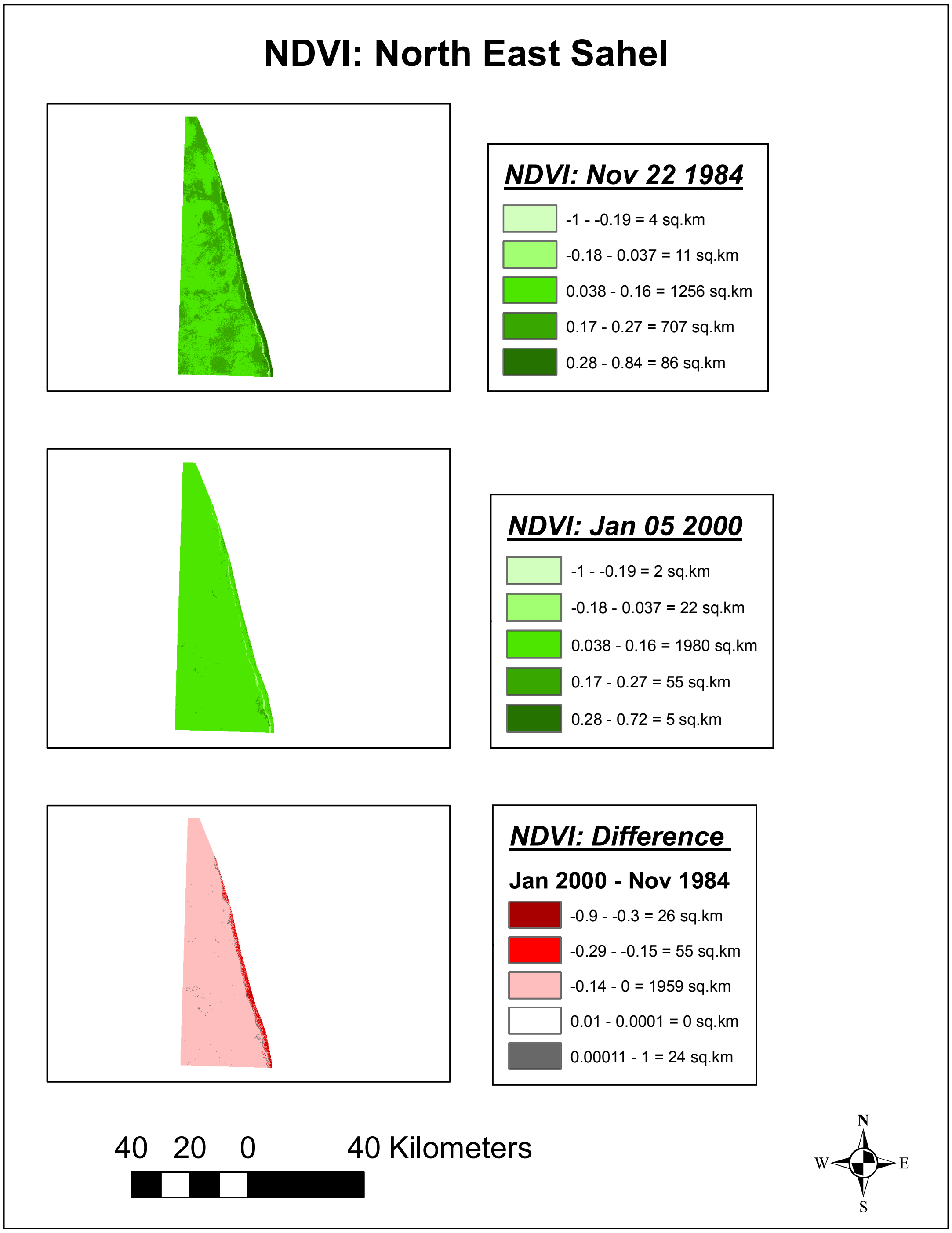

Figure 3.24 NDVI in study area 5: North East Sahel (coastal plains zone). There was an overall decrease in the NDVI value in all the study area in 2000 from those of 1984 except for some areas in the coastal fringes (eastern parts) of the study area.

Table 3.17 Percent vegetation change in study area 5 (North East Sahel). Note the decrease in the highland shrub and forest classes and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1984	%of total area in this NDVI range in 2000	% 2000 - % 1984
Desert ((-1) - 0.16)	62	97	35
Highland shrub (0.17 - 0.27)	34	3	-31
Forest (0.28 - 1)	4	0	-4
	100	100	

Generally, there was a decrease in NDVI vegetation values except in the coastal areas (Figure 3.22). The mean NDVI values obtained for November 22, 1984, and January 05, 2000, were -0.08 and -0.02, respectively. Standard deviations were 0.08 and 0.05, respectively. NDVI vegetation values decreased on 99% of the study area and increased on 1% (Figure 3.24). The coefficients of variability were 1.00 and 2.5, respectively, indicating that the 2000 data were more variable than those of 1984. The highland shrub vegetation class decreased by 92% relative to the 1984 leading to the increase in the desert class (Table 3.17)

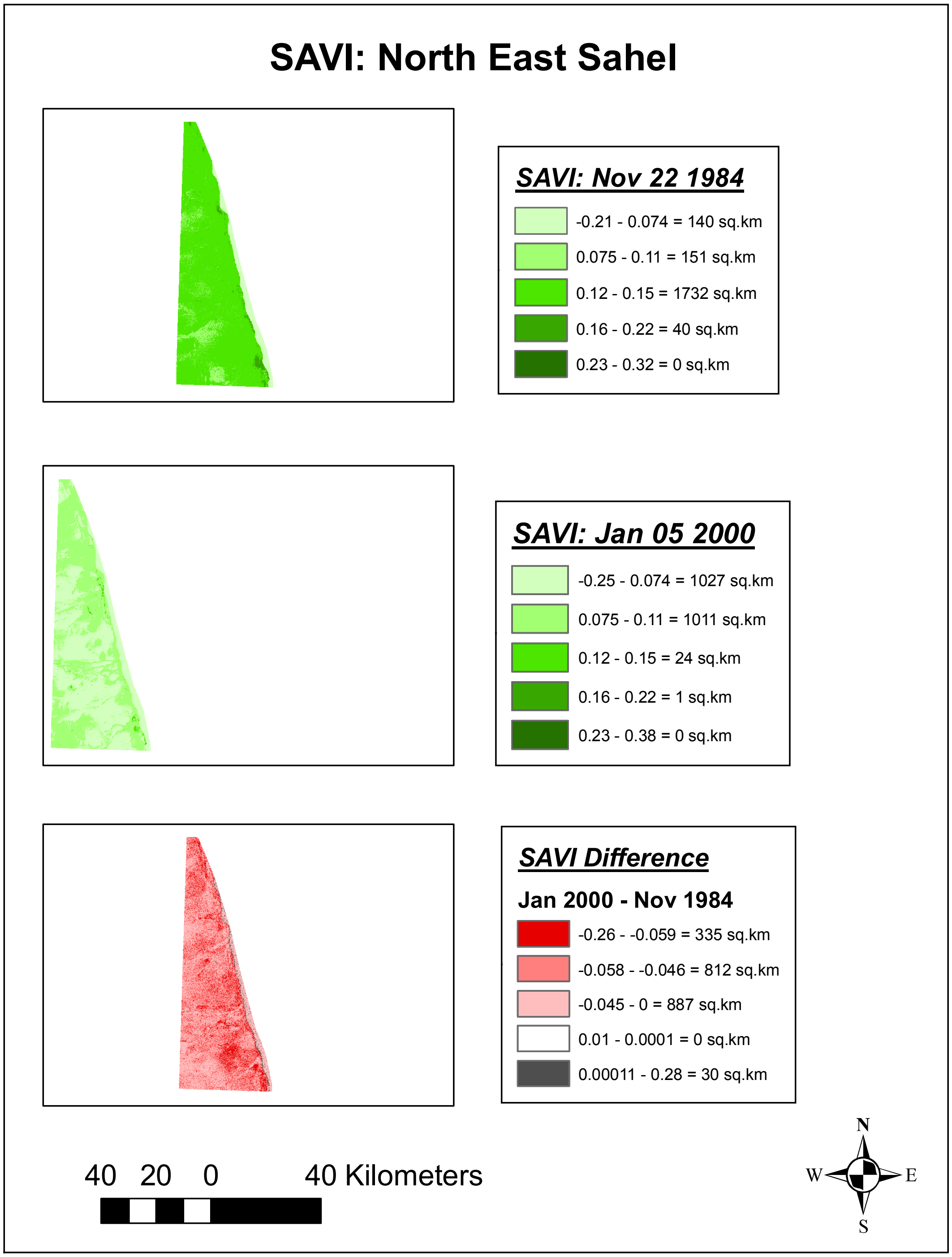

Figure 3.25 SAVI in study area 5: North East Sahel (coastal plains zone). There was an overall decrease in the SAVI value in all the study area in 2000 from those of 1984 except for some areas in the coastal fringes (eastern parts) of the study area.

Table 3.18 SAVI percent vegetation change in North East Sahel. Note the decrease in the highland shrub class and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1984	% of total area in this SAVI range in 2000	% 2000 - % 1984
Desert ((-1) - 0.11)	14	99	85
Highland shrub (0.11 - 0.22)	86	1	-85
Forest (0.23 - 1)	0	0	0
Total	100	100	

Similar to the NDVI, there was a decrease in SAVI vegetation values except in the coastal areas (Figure 3.25). The mean SAVI values obtained for November 22, 1984, and January 5, 2000, were -0.004 and -0.001. Standard deviations were 0.04 and 0.02, respectively. The coefficients of variability were 10.00 and 20.00 respectively; showing that there was more (unlike the NDVI) variability among the datasets in 2000 than in 1984. SAVI vegetation values decreased on 99% of the study area and increased on 1% (Figure 3.25). The results and analysis from SAVI were very similar to the NDVI. The highland shrub vegetation class decreased by 100% relative to the 1984 leading to the increase in the desert class (Table 3.18).

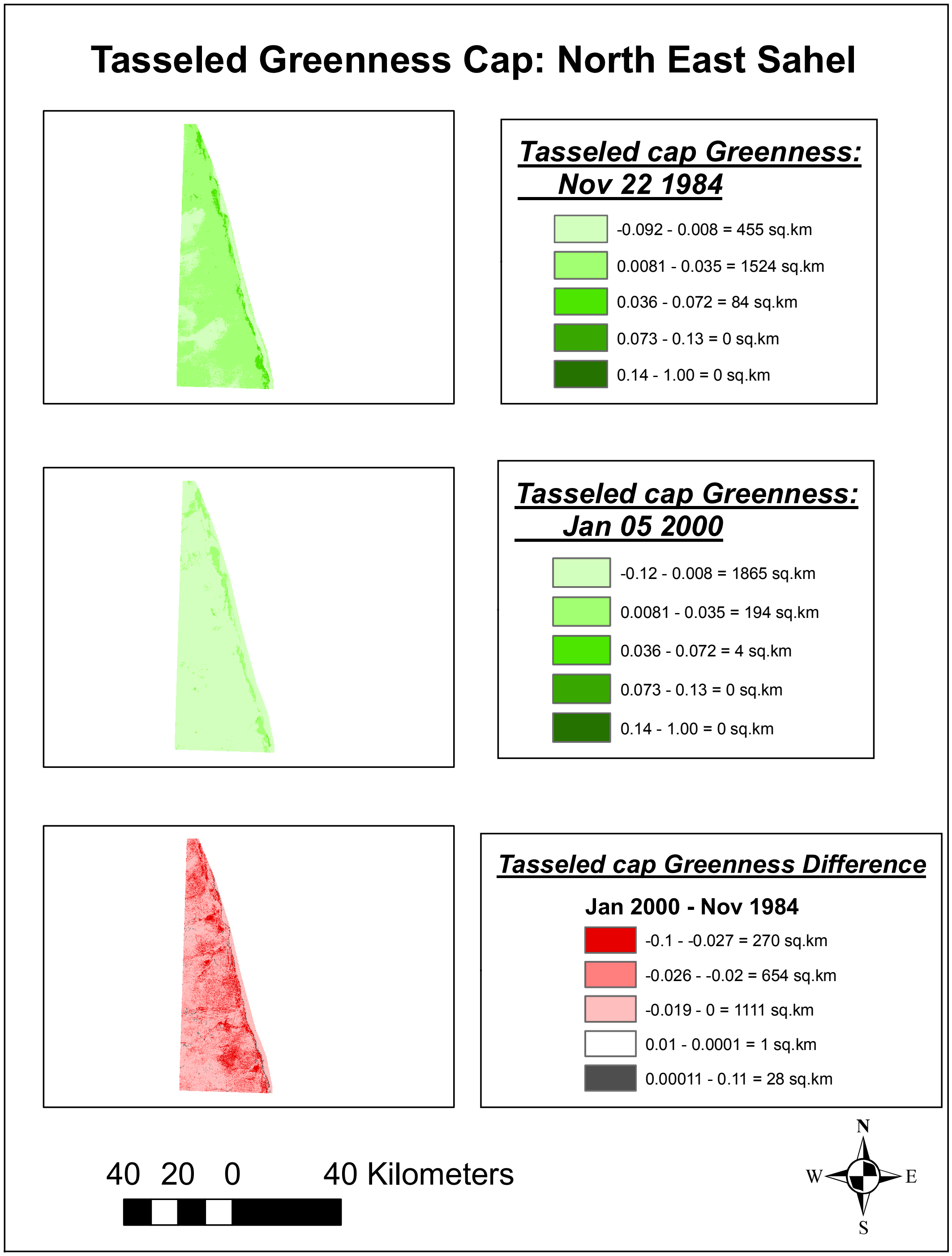

Figure 3.26 Tasseled Greenness analysis in North East Sahel in study area 5: (coastal plains zone). There was an overall decrease in the Tasseled Greenness value in all the study area in 2000 from those of 1984 except for some areas in the coastal fringes (eastern parts) of the study area.

Table 3.19 Tasseled Greenness percent vegetation change in North East Sahel. Note the decrease in the highland shrub class and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1984	% of total area in this TC Greenness range in 2000	% 2000 - % 1984
Desert ((-1) - 0.035)	96	100	4
Highland shrub (0.036 - 0.13)	4	0	-4
Forest (0.073 - 1)	0	0	0
	100	100	

Similar to the NDVI and SAVI, there was a decrease in Tasseled Greenness vegetation (Figure 3.26). But unlike the NDVI and SAVI the increase in coastal vegetation values was not visible on the TC Greenness image. The mean Tasseled Greenness values obtained for November 22, 1984, and January 05, 2000, were -0.003 and -0.03, respectively, with equal standard deviations of 0.005. The coefficients of variability were 1.67 and 0.17, respectively. Similar to the SAVI but unlike the NDVI the coefficients of variability indicated that the 1984 datasets have more variability than the 2000 data. Tasseled Greenness vegetation values decreased on 99% of the study area, which was a very similar value as the NDVI and SAVI (Figure 3.26). The highland shrub vegetation class decreased by 78% relative to the 1984 leading to the increase in the desert class (Table 3.19).

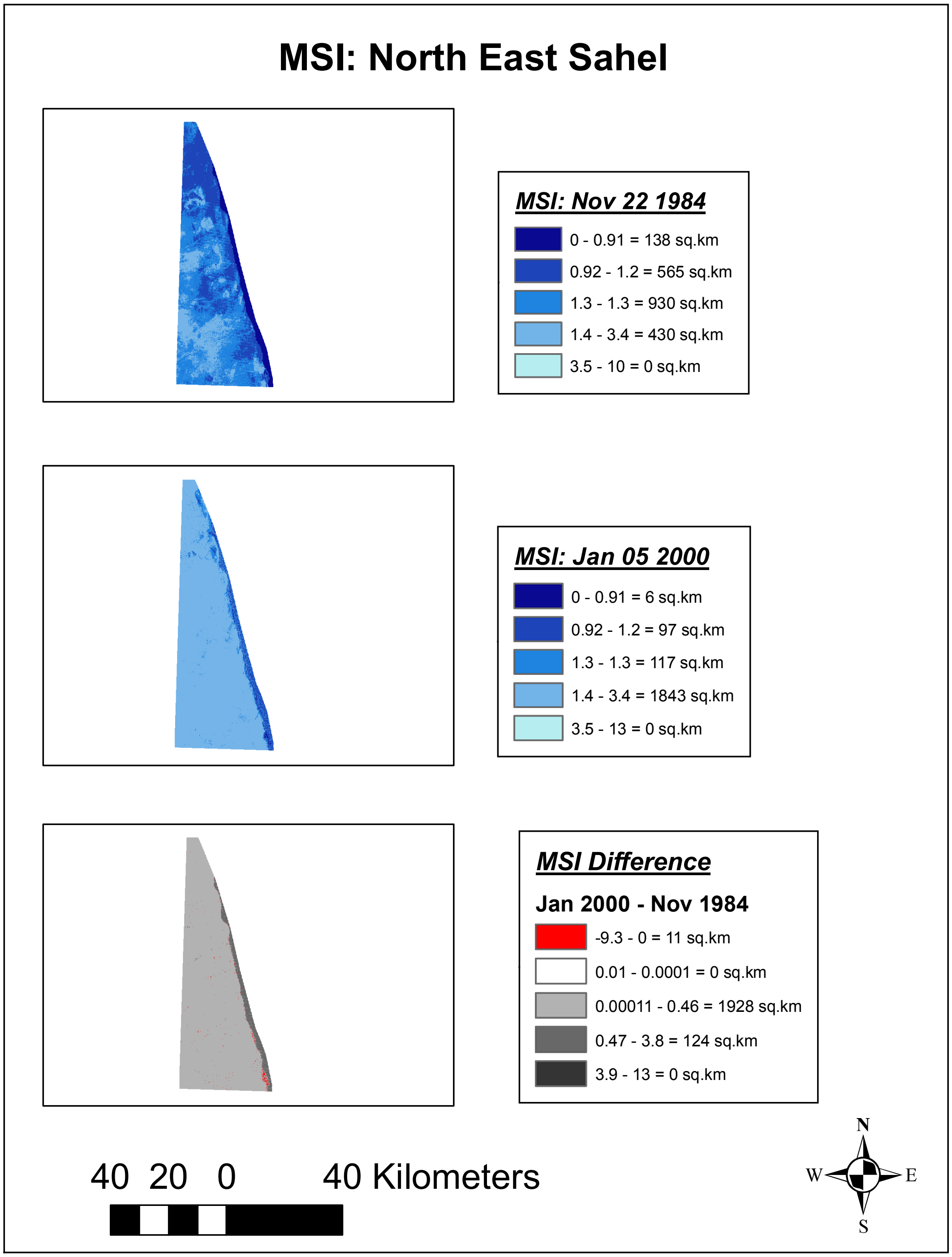

Figure 3.27 MSI analyses in study area 5: North East sahel (coastal plains zone). There was an overall increase in the MSI value in all the study area in 2000 from those of 1984 except on some coastal areas (eastern parts).

There was similarity in the results obtained by the MSI and TC Greenness in study area 5. There was an overall increase in MSI on 99% of the study area (Figure 3.27) .The overall increase in moisture stress corresponded well with the decrease in vegetation values as shown by the NDVI, SAVI, and TC Greenness. As in the MSI, the TC Wetness values showed a decrease in wetness value on 82% of the study area (Figure 3.28). The decrease in wetness also corresponded with the decrease in the vegetation values as shown by the NDVI, SAVI, and TC Greenness (and also increases in moisture stress as shown by MSI).

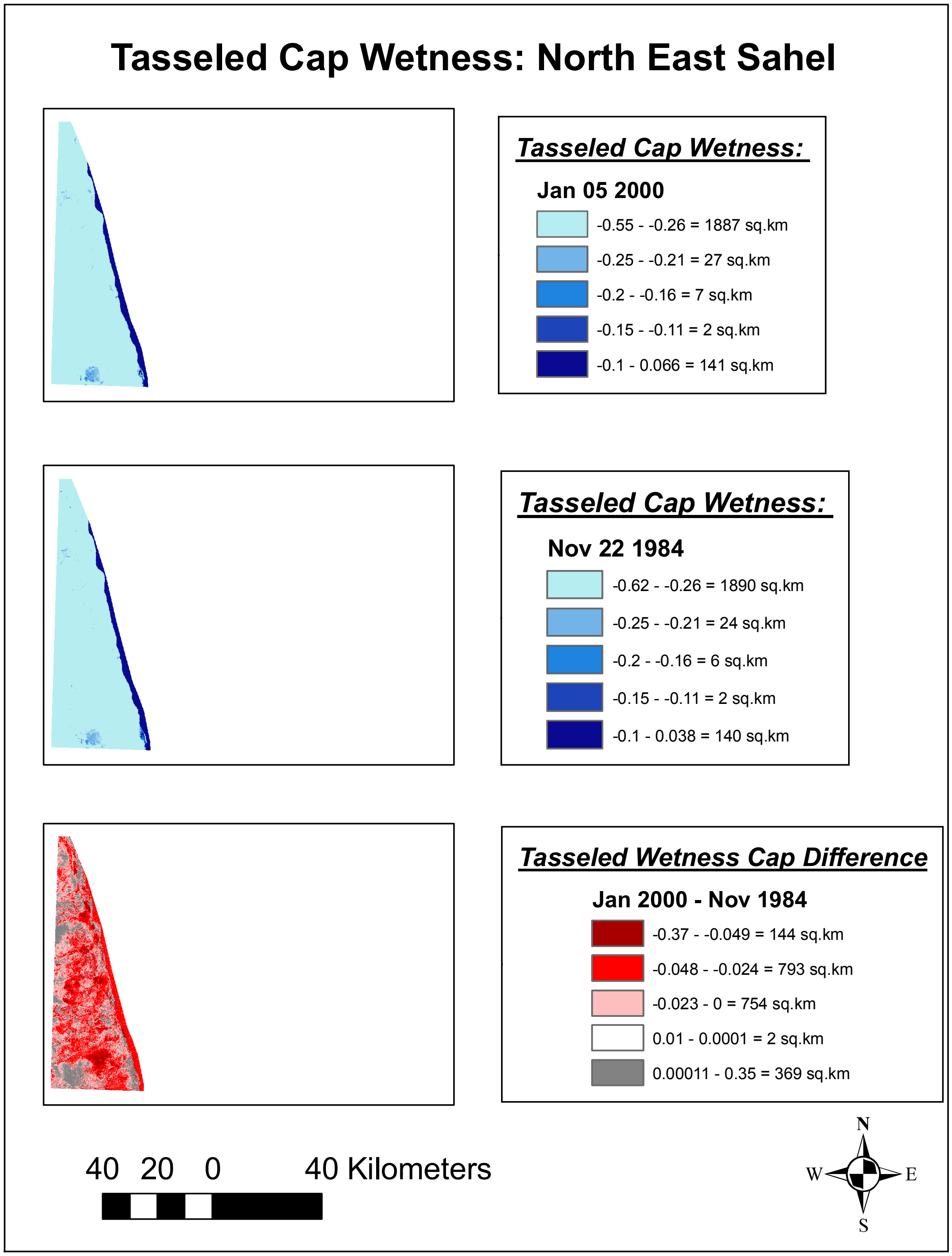

Figure 3.28 TC Wetness analyses in study area 5: North East Sahel (coastal plains zone). There was a general decrease in the TC Wetness values in all the study area in 2000 from those of 1984.

3.2.6 Study area 6: West Sahel

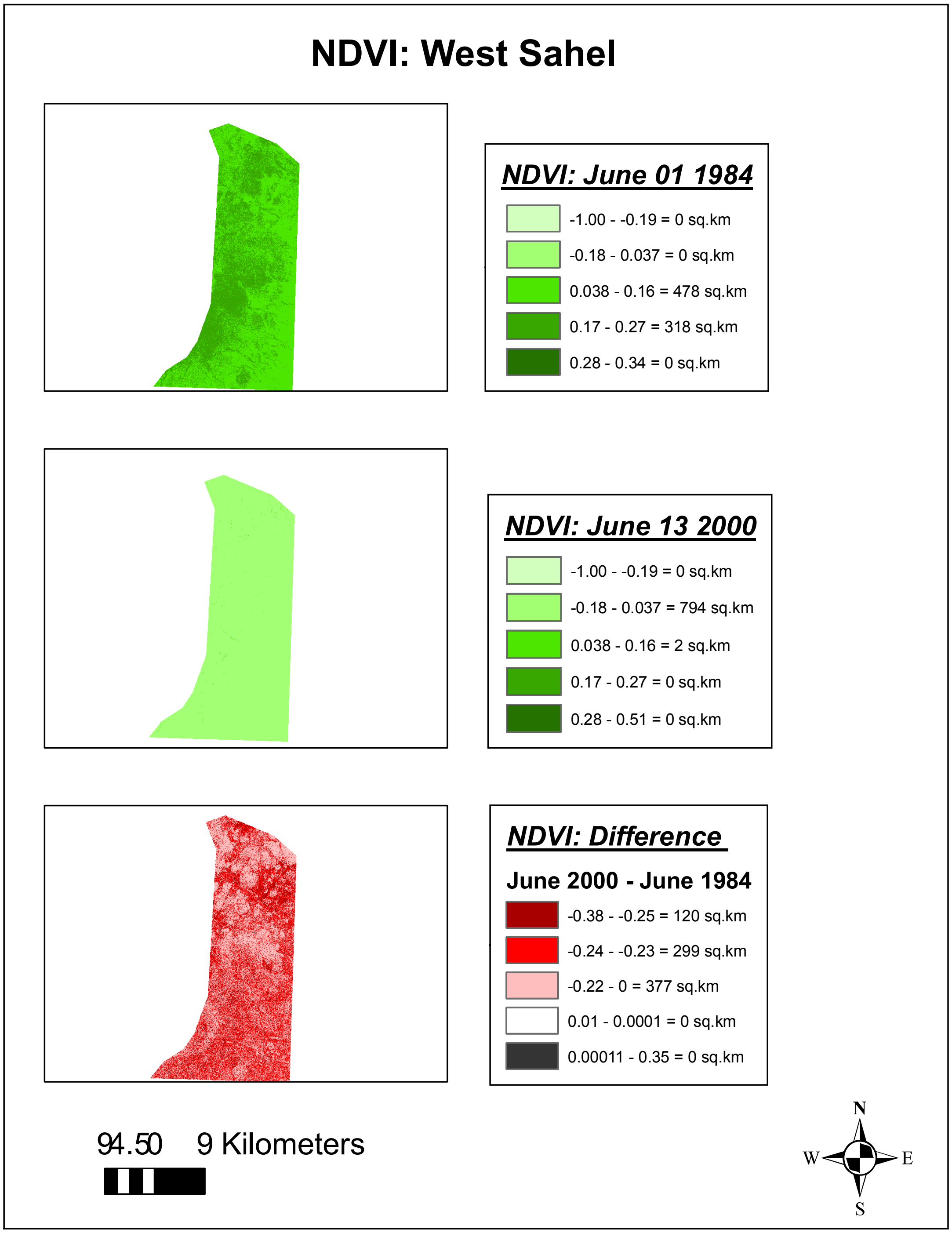

Figure 3.29 NDVI difference analysis analyses in study area 6: West Sahel (North Western Lowland zone). There was an overall decrease in the NDVI value in all the study area in 2000 from those of 1984.

Table 3.20 Percent vegetation change in study area 6 (West Sahel). Note the high decrease in the highland shrub and forest classes and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1984	% of total area in this NDVI range in 2000	% 2000 - % 1984
Desert ((-1) - 0.16)	60	100	40
Highland shrub (0.17 - 0.27)	40	0	-40
Forest (0.28 - 1)	0	0	0
	100	100	

Generally, there was a decrease in NDVI vegetation values (Figure 3.29).The mean NDVI values obtained for June 1, 1984, and June 13, 2000, were 0.14 and -0.08, respectively. Standard deviations were 0.02 and 0.03, respectively. The coefficients of variability were 0.14 and 0.38, respectively, indicating that the 1984 NDVI values were more variable than those of 2000. NDVI vegetation values decreased on 100% of the study area and increased on 0% (Figure 3.29). The highland shrub and forest areas decreased by 100% of their 1984 level in 2000 (Table 3.20).

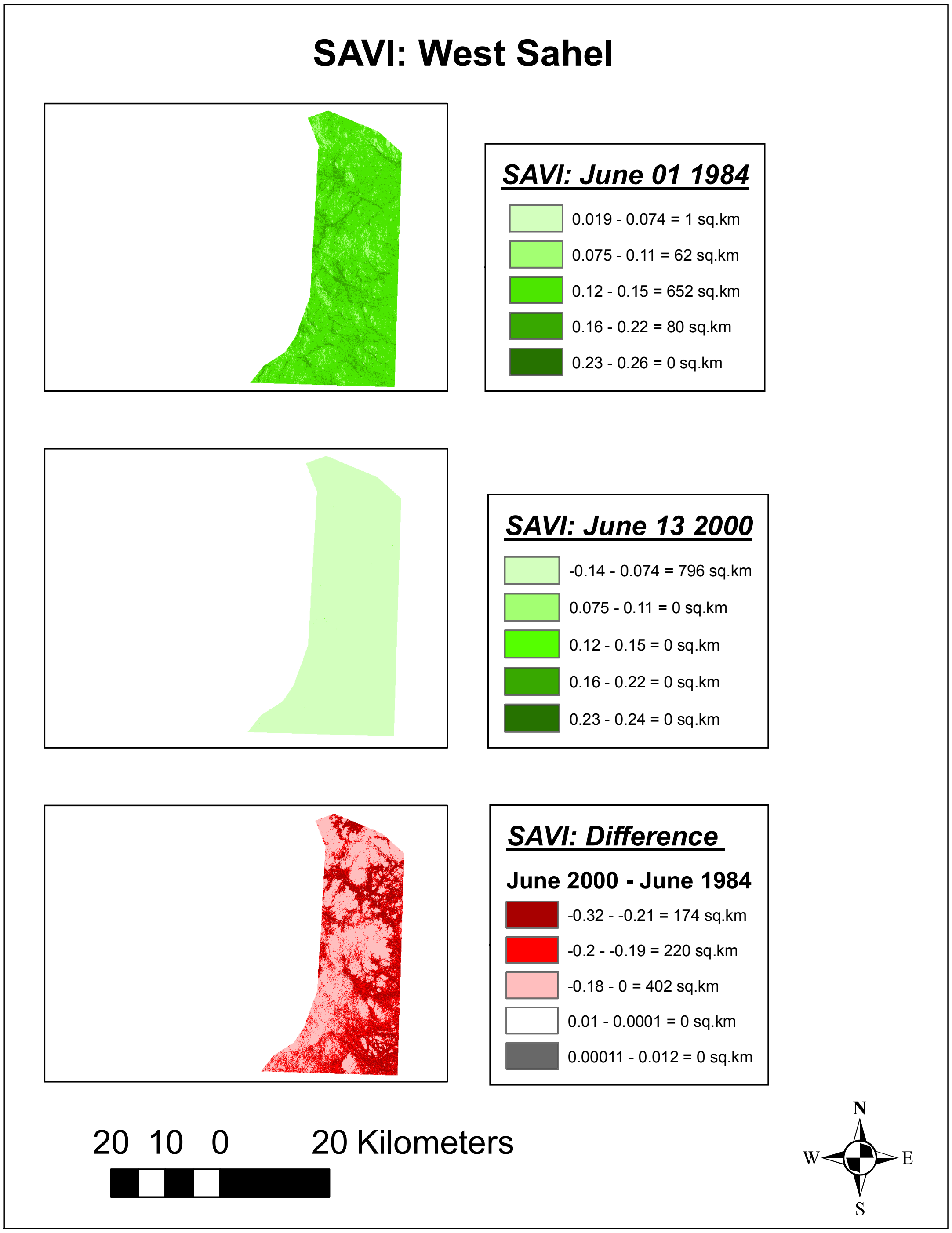

Figure 3.30 SAVI difference analysis analyses in study area 6: West Sahel (North Western Lowland zone). There was an overall decrease in the SAVI value in all the study area in 2000 from those of 1984.

Table 3.21 SAVI percent vegetation change in West Sahel. Note the high decrease in the highland shrub and forest classes and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1984	% of total area in this SAVI range in 2000	% 2000 - % 1984
Desert ((-1) - 0.11)	8	100	92
Highland shrub (0.12 - 0.22)	92	0	-92
Forest (0.23 - 1)	0	0	0
Total	100	100	

Generally, as in the NDVI, there was a decrease in SAVI vegetation values except in the coastal areas (Figure 3.30).The mean SAVI values obtained for June 1, 1984, and June 13, 2000, were 0.11 and -0.06, respectively. Standard deviations were 0.03 and 0.04, respectively. The coefficients of variability were 0.18 and 0.50, respectively, indicating that the 2000 SAVI values were more variable than those of 1984. SAVI vegetation values decreased on 100% of the study area compared to those of 1984 (Fig 3.30). Although very similar to the NDVI, the SAVI image showed that there was a pronounced decrease in the western portion of the study area relative to NDVI. The highland shrub and forest areas decreased by 100% of their 1984 level in 2000 (Table 3.21).

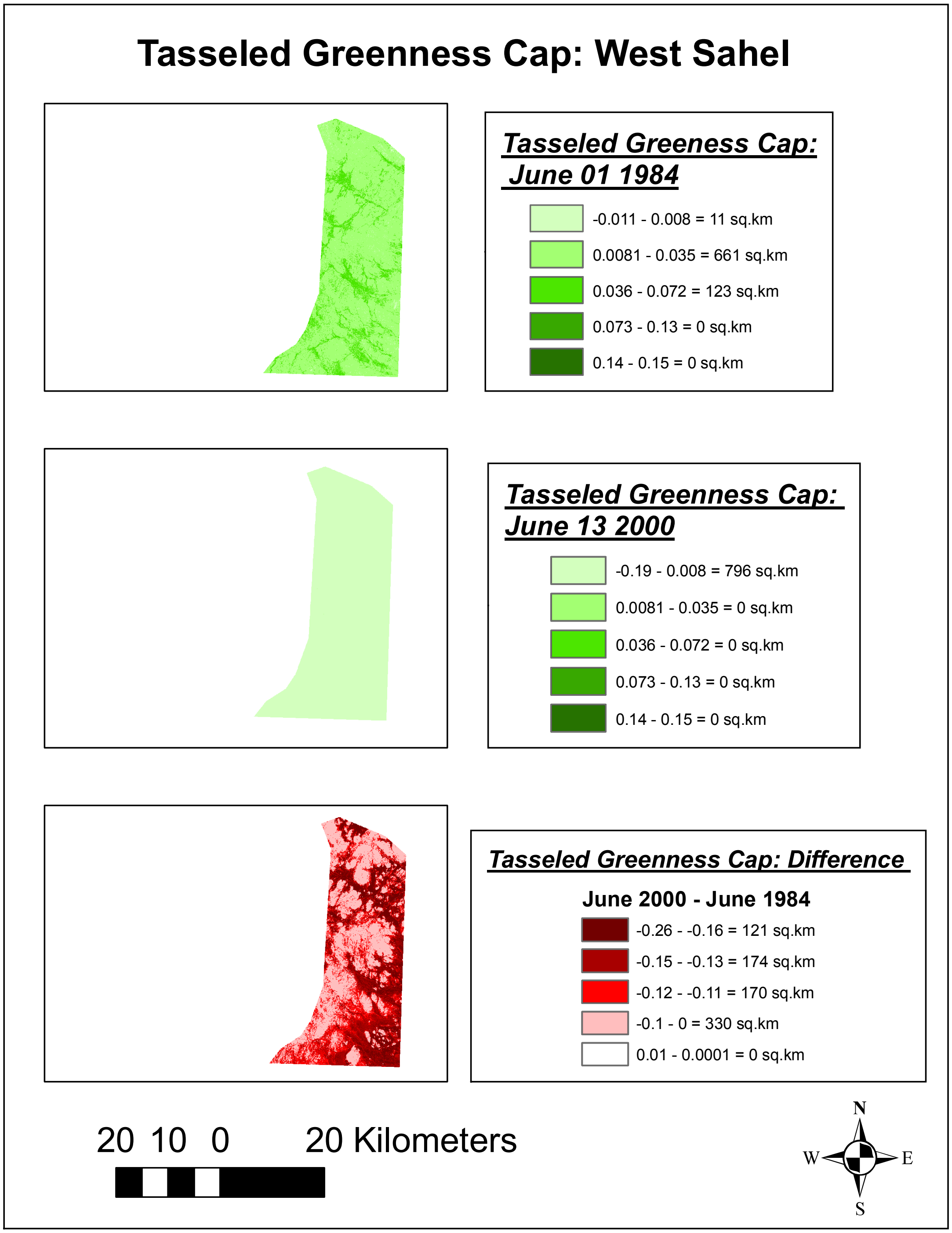

Figure 3.31 Tasseled Greenness difference analysis analyses in study area 6: West Sahel (North Western Lowland zone). There was an overall decrease in the Tasseled Greenness value in all the study area in 2000 from those of 1984.

Table 3.22 : Tasseled Greenness percent vegetation change in West Sahel. Note the high decrease in the highland shrub class and the increase in the desert class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1984	% of total area in this TC Greenness range in 2000	% 2000 – % 1984
Desert ((-1) - 0.035)	62	100	38
Highland shrub (0.036 - 0.072)	38	0	-38
Forest (0.073 - 1)	0	0	0
	100	100	

Generally, as in the NDVI and SAVI, there was a decrease in the Tasseled Greenness vegetation values except in the coastal areas (Figure 3.31). The mean Tasseled Greenness values obtained for June 1, 1984, and June 13, 2000, were 0.02 and –0.09, respectively. Standard deviations were 0.01 and 0.03, respectively. The coefficients of variability were 0.50 and 0.33, respectively, indicating unlike the NDVI and SAVI that the 1984 Tasseled Greenness values were more variable among each other than those of 2000. Similar to the NDVI and SAVI, Tasseled Greenness value decreased on 100% of the study area (Figure 3.31). The patterns of vegetation decrease in 2000 relative to 1984 were similar to those of the SAVI (highest decreases were observed in the western portion of the study area). The highland shrub and forest areas decreased by 100% of their 1984 level in 2000 (Table 3.22).

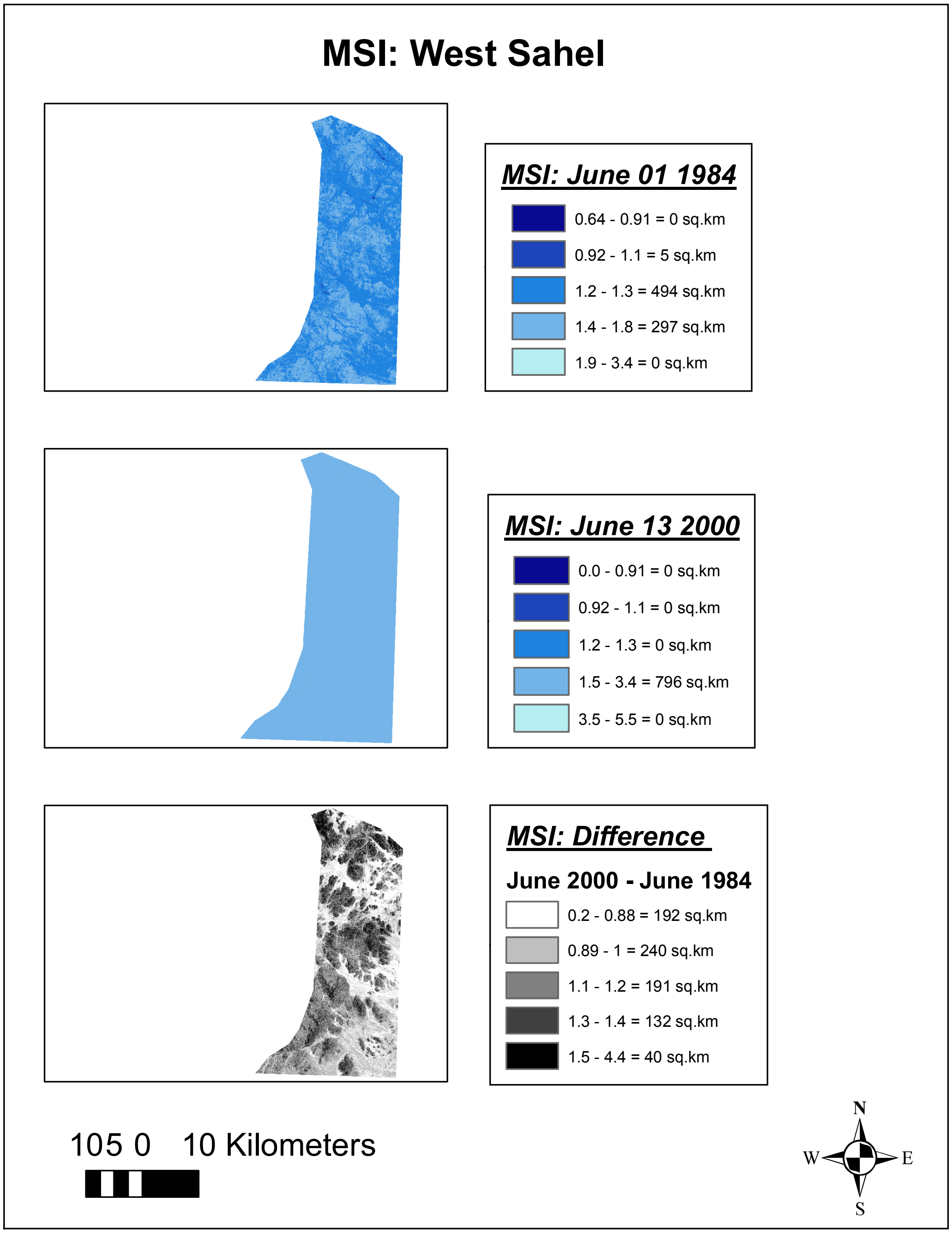

Figure 3.32 MSI difference analysis analyses in study area 6: West Sahel (North Western Lowland zone). There was an overall increase in the MSI value in all the study area in 2000 from those of 1984.

There was a similarity in the results obtained by the MSI and Tasseled Greenness in study area 6. There was an overall increase in MSI on 100% of the study area (Figure 3.32). Similar to the MSI, the TC Wetness value showed a decrease in wetness value on 99% of the study area (Figure 3.33). The spatial pattern conveying lesser moisture stress (MSI) or decrease in wetness as shown in the 1984 data relative to the 2000 data corresponded well with that shown by the three vegetation indices.

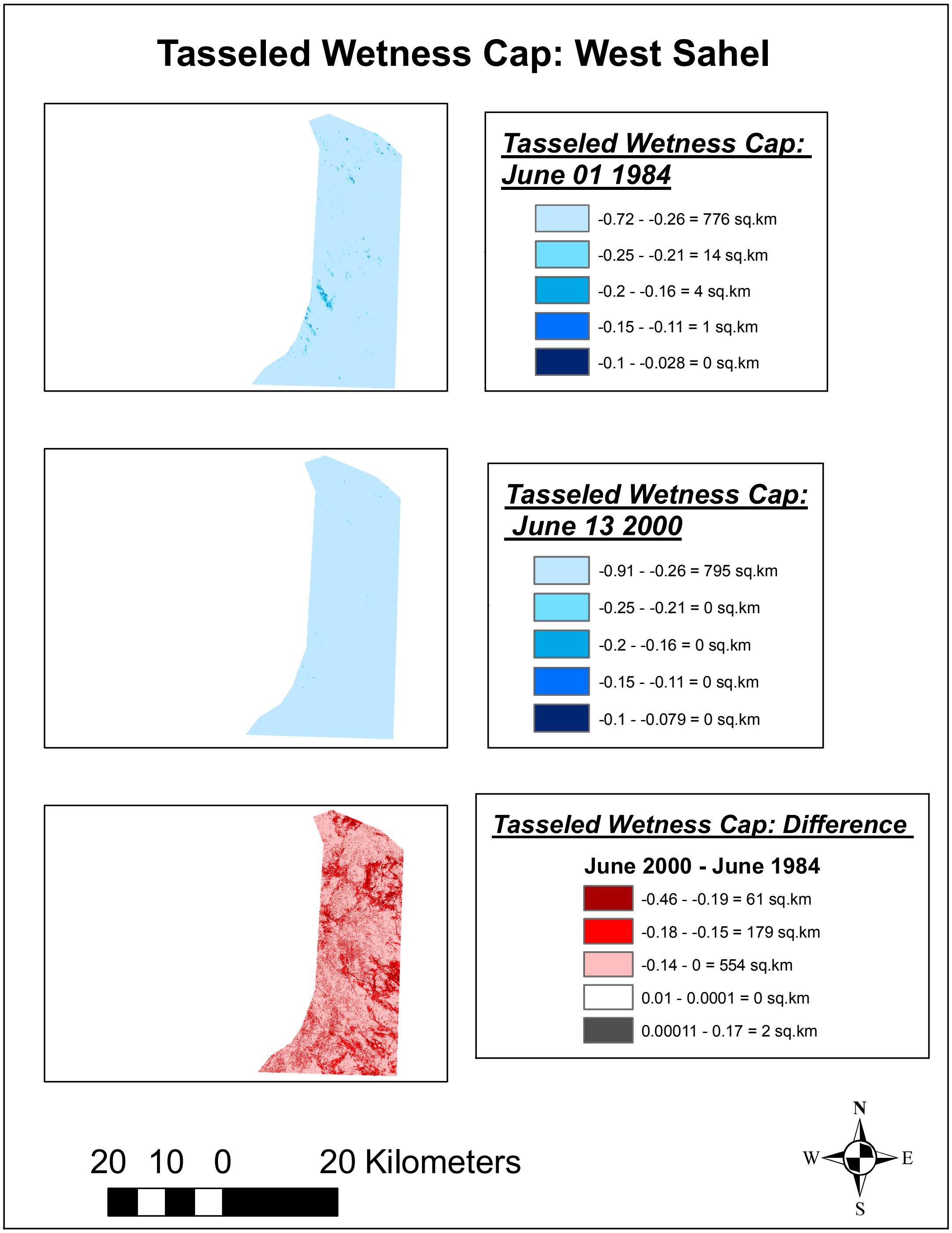

Figure 3.33 TC Wetness difference analysis analyses in study area 6: West Sahel (North Western Lowland zone). There was an overall decrease in the Tasseled Greenness values in all the study area in 2000 from those of 1984.

3.2.7 Study area 7: Southern Highland

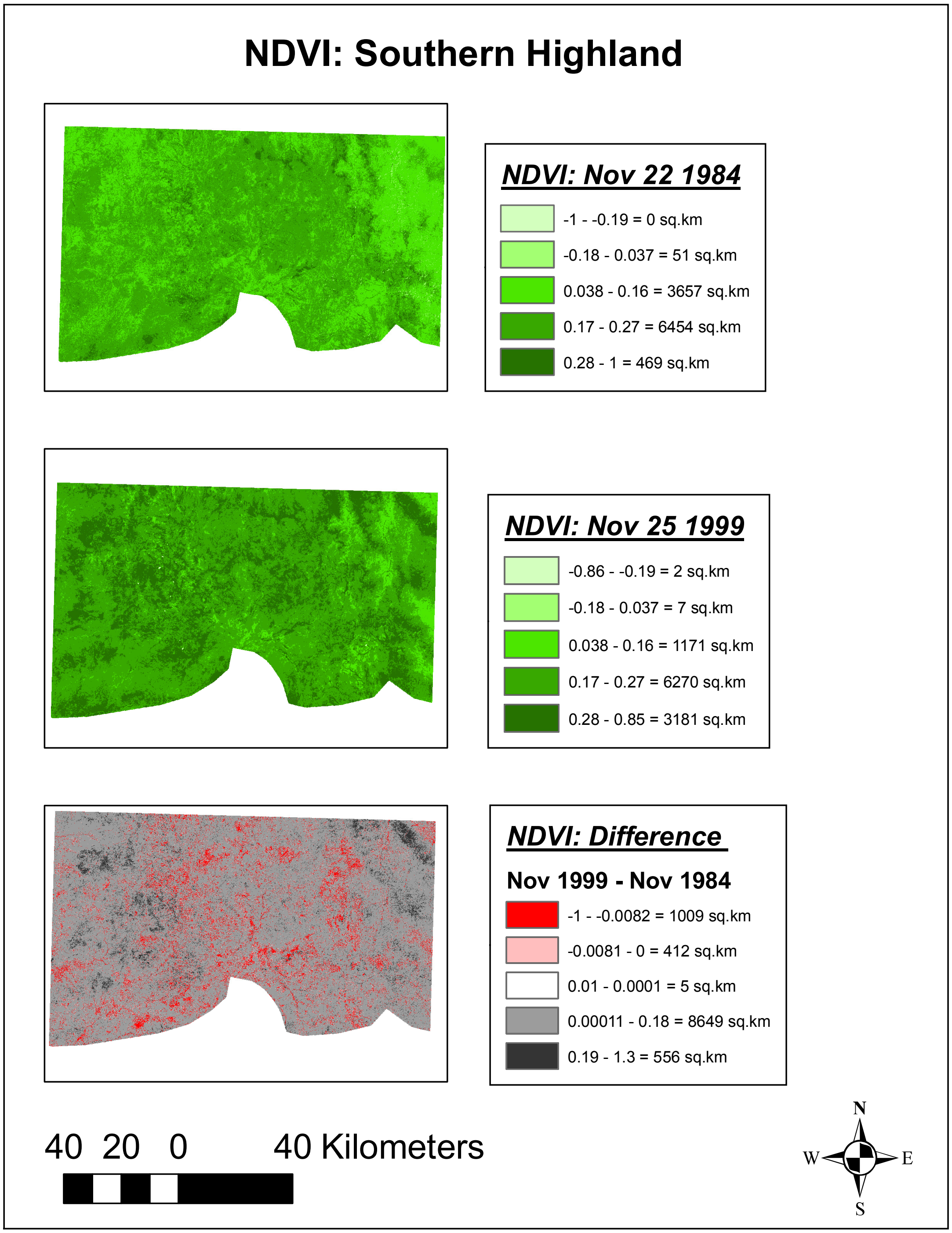

Figure 3.34 NDVI difference analysis analyses in study area 7: Southern Highland (Western Escarpment and Central Highland zones). There was an overall increase in the NDVI values in all the study area in 1999 from those of 1984.

Table 3.23 NDVI percent vegetation change in Southern Highlands (Southern part). Note the high decrease in the desert class and the increase in the forest class.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI in 1984	% of total area in this NDVI range in 1999	% 1999 - % 1984
Desert ((-1) - 0.16)	35	11	-23
Highland shrub (0.17 - 0.27)	61	59	-2
Forest (0.28 - 1)	4	30	26
	100	100	

Generally, there was an increase in the NDVI vegetation values (Figure 3.34).The mean NDVI values obtained for November 22, 1984, and November 25, 1999, were 0.18 and 0.24, respectively. Standard deviations were 0.05 and 0.07, respectively. The coefficients of variability were 0.28 and 0.29, indicating that the 1999 and 1984 NDVI values were similarly variable. The mean thus can be used as a good indicator in the vegetation value comparison. NDVI vegetation values increased on 87% of the study area and decreased on 13%. There is not much spatial pattern in the increase (for example the highest decreases in NDVI values were found in pockets in northeastern, southwestern, and central parts of the study area). The area of forest increased by 68% of its 1984 level in 1999 (Table 3.23).

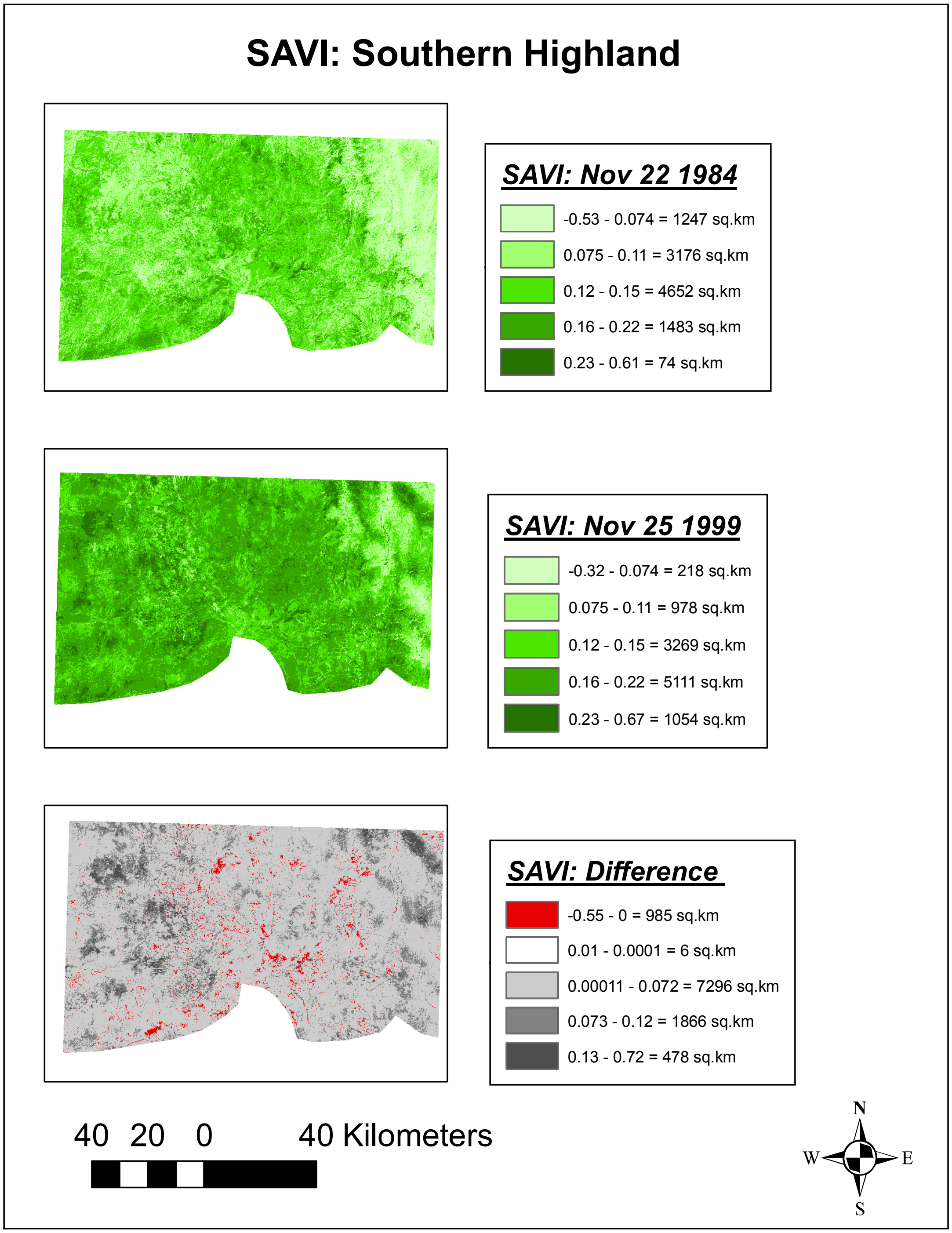

Figure 3.35 SAVI difference analysis analyses in study area 7: Southern Highland (Western Escarpment and Central Highland zones). There was an overall increase in the SAVI values in all the study area in 1999 from those of 1984.

Table 3.24 SAVI percent vegetation change in Southern highlands. Note the high decrease in the desert class and the increase in the highland shrub and forest classes.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1984	% of total area in this SAVI range in 1999	% 1999 - % 1984
Desert ((-1) -0.11)	41	11	-30
Highland shrub (0.12 - 0.22)	58	79	21
Forest (0.23 - 1)	1	10	9
Total	100	100	

Generally, there was an increase in the SAVI vegetation values (Figure 3.35). The mean SAVI values obtained for November 22, 1984, and November 25, 1999, were 0.12 and 0.16, respectively. Standard deviations were 0.04 and 0.05, respectively. The coefficients of variability were 0.33 and 0.31 respectively, indicating that the 1984 SAVI values were slightly more variable among each other than those of 1999. SAVI vegetation values increased on 91% of the study area in 1999 from those of 1984 (Figure 3.35). There was almost no difference in using either NDVI or SAVI in assessing vegetation values in the study area. According to the SAVI, desert class decreased by 73% in 1999 in study area 7 compared to 1984 (Table 3.24).

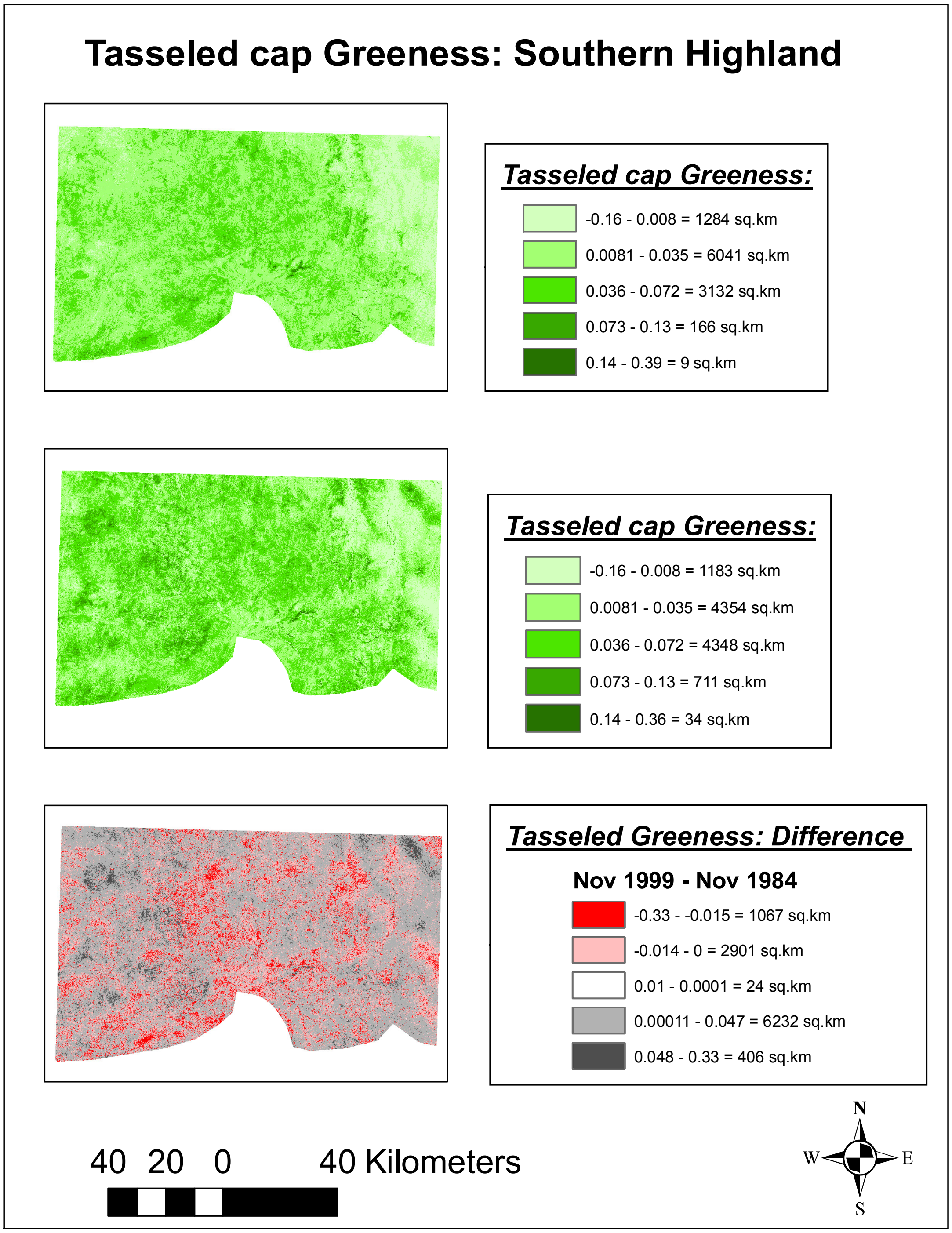

Figure 3.36 Tasseled Greenness difference analysis analyses in study area 7: Southern Highland (Western Escarpment and Central Highland zones). There was an overall increase in the Tasseled Greenness values in all the study area in 1999 from those of 1984.

Table 3.25 Tasseled Greenness percent vegetation change in Southern Highland. Note the high decrease in the desert class and the increase in the highland shrub and forest classes.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this TC Greenness range in 1984	% of total area in this TC Greenness range in 1999	% 1999 - % 1984
Desert ((-1) - 0.035)	69	52	-17
Highland shrub (0.036 - 0.072)	29	41	12
Forest (0.073 - 1)	2	7	5
	100	100	

Generally, there was an increase in Tasseled Greenness vegetation values (Figure 3.36). The mean TC Greenness values obtained for November 22, 1984 and November 25, 1999, were 0.03 and 0.04, respectively with equal standard deviations of 0.02. The coefficients of variability were 0.67 and 0.50, respectively, indicating that the 1984 Tasseled Greenness values were more variable among each other than those of 1999. Tasseled Greenness vegetation values increased on 62% of the study area and decreased on 37% in 1999 from those of 1984. There was more similarity between the NDVI and SAVI in the level of vegetation value increase in 1999, while the TC Greenness showed a lower amount increase than either. The desert class decreased by 24% in 1999 from those of 1984, while the highland shrub and forest classes increased (Table 3.25).

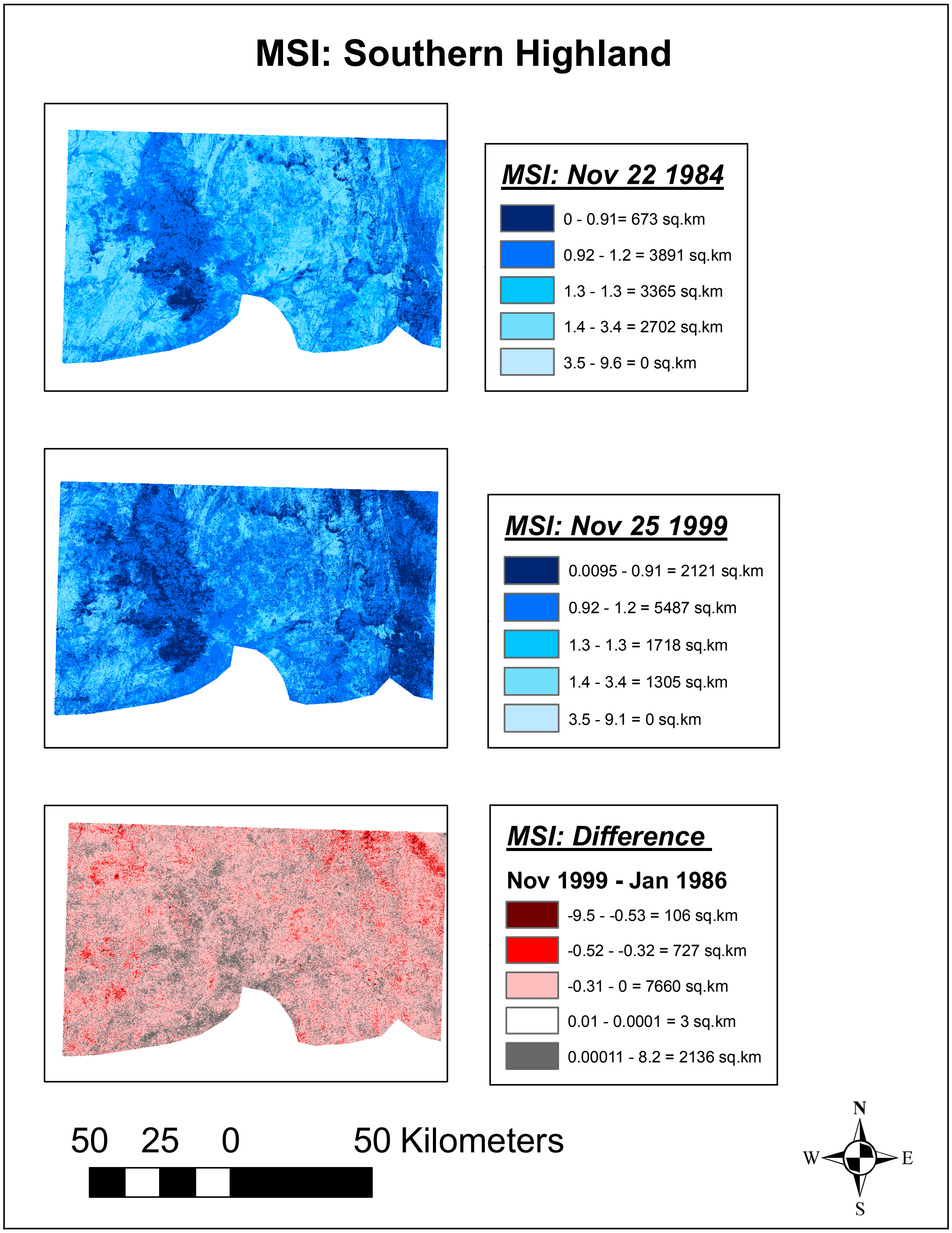

Figure 3.37 MSI difference analysis analyses in study area 7: Southern Highland (Western Escarpment and Central Highland zones). There was an overall decrease in the MSI value in all the study area in 1999 from those of 1984.

There was a slight dissimilarity in the results obtained by the MSI and TC Wetness in study area 7. MSI values decreased on 80% of the study area, while TC Wetness values increased on 54% in 1999 from those of 1984 (Figure 3.37 and 3.38). The result from MSI (decrease in moisture stress) did correspond well with the increase in vegetation as observed by the three vegetation indices. The result from the Tasseled Greenness value (54% or about half of the study area showed increase in wetness) did correspond slightly with the increase in vegetation as portrayed by the three vegetation indices.

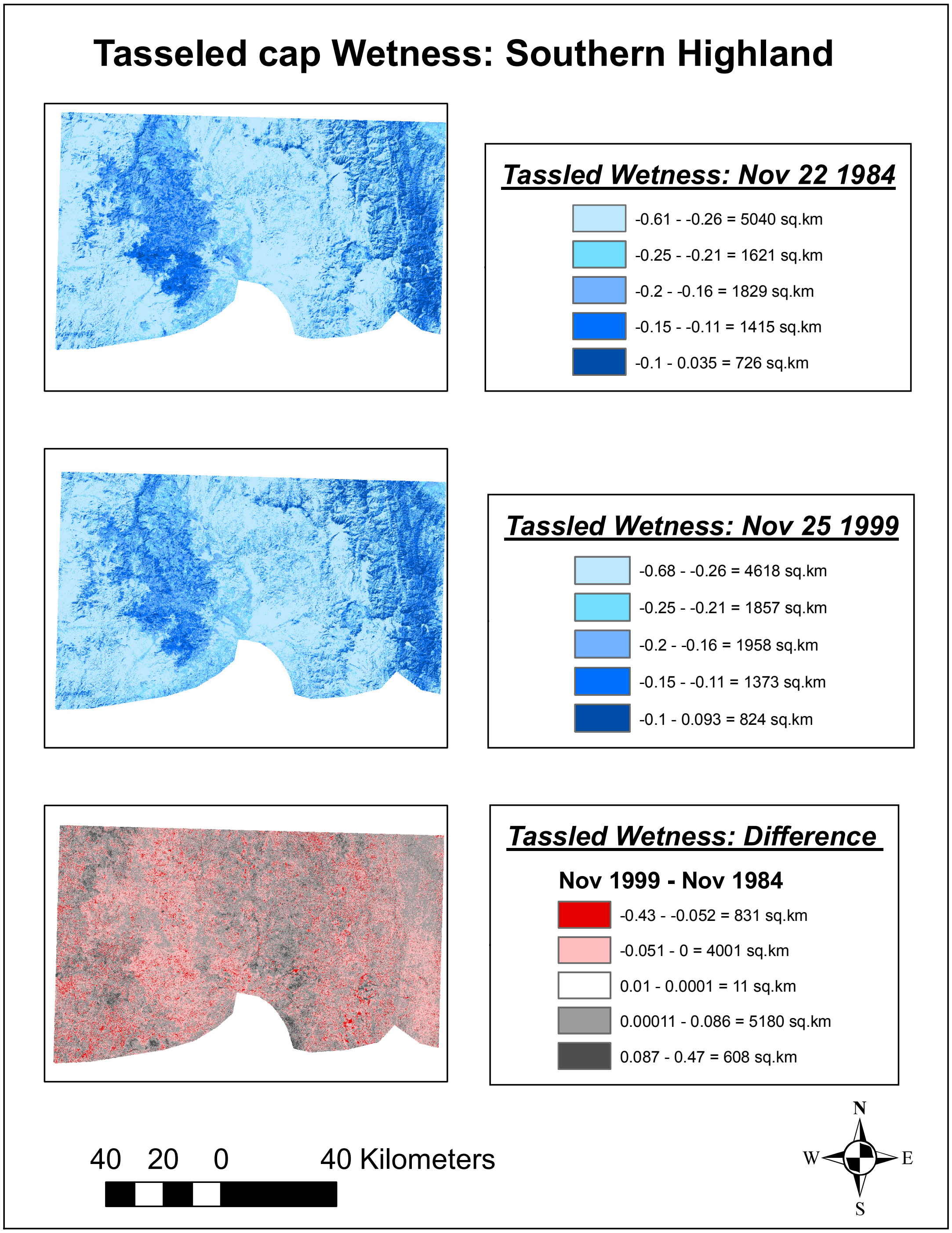

Figure 3.38 TC Wetness difference analysis analyses in study area 7: Southern Highland (Western Escarpment and Central Highland zones). Generally there was a slightly higher increase in the TC Wetness values in all the study area in 1999 from those of 1984.

3.2.8 Study area 8: Gash Barka

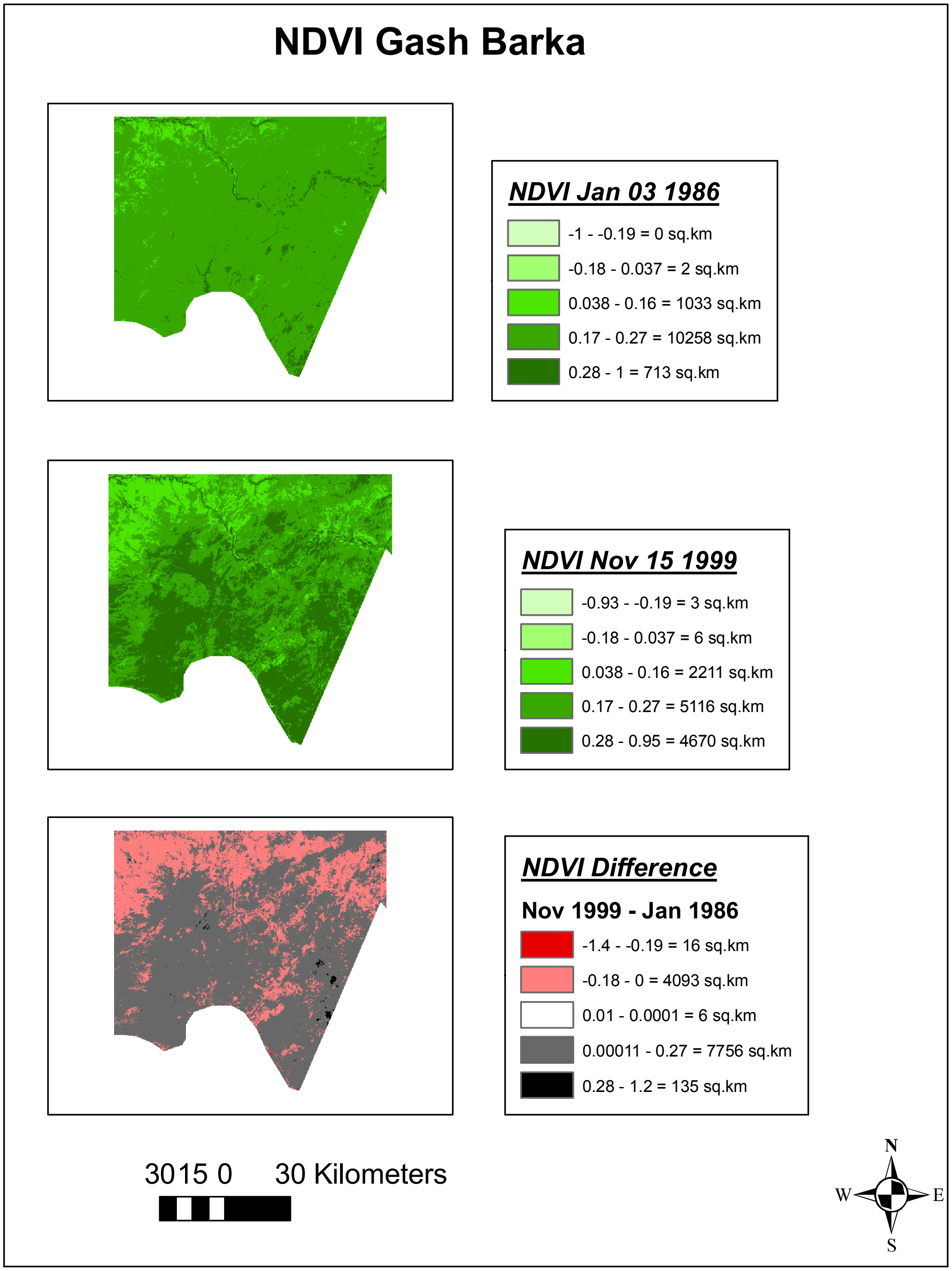

Figure 3.39 NDVI difference analysis analyses in study area 8: Gash Barka (South Western Lowland zone). There was an overall increase in the NDVI value in southern and central parts of the study area, but decrease elsewhere (especially in the northern portions) in 1999 from those of 1986.

Table 3.26 NDVI percent vegetation change in Gash Barka (South Western Lowland). Note the high decrease in the highland shrub class and the increase in the forest and desert classes.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this NDVI range in 1986	% of total area in this NDVI range in 1999	% 1999 - % 1986
Desert ((-1) - 0.16)	9	18	9
Highland shrub (0.17 - 0.27)	85	43	-42
Forest (0.28 - 1)	6	39	33
	100	100	

The mean NDVI values obtained for January 3, 1986, and November 15, 1999, were 0.21 and 0.25, respectively. Standard deviations were 0.04 and 0.10, respectively. The coefficients of variability were 0.19 and 0.40, respectively, indicating that the 1999 NDVI values were more variable among each other than of 1986. NDVI vegetation values increased on 66% of the study area and decreased on 34% in 1999 from those of 1986 (Figure 3.39). Most of the increase in the NDVI values was in the forest class (74% forest class of the 1986 level) while the decrease was in the highland shrub class where there was a 100% rate of decrease relative to the 1984 levels (Table 3.26).

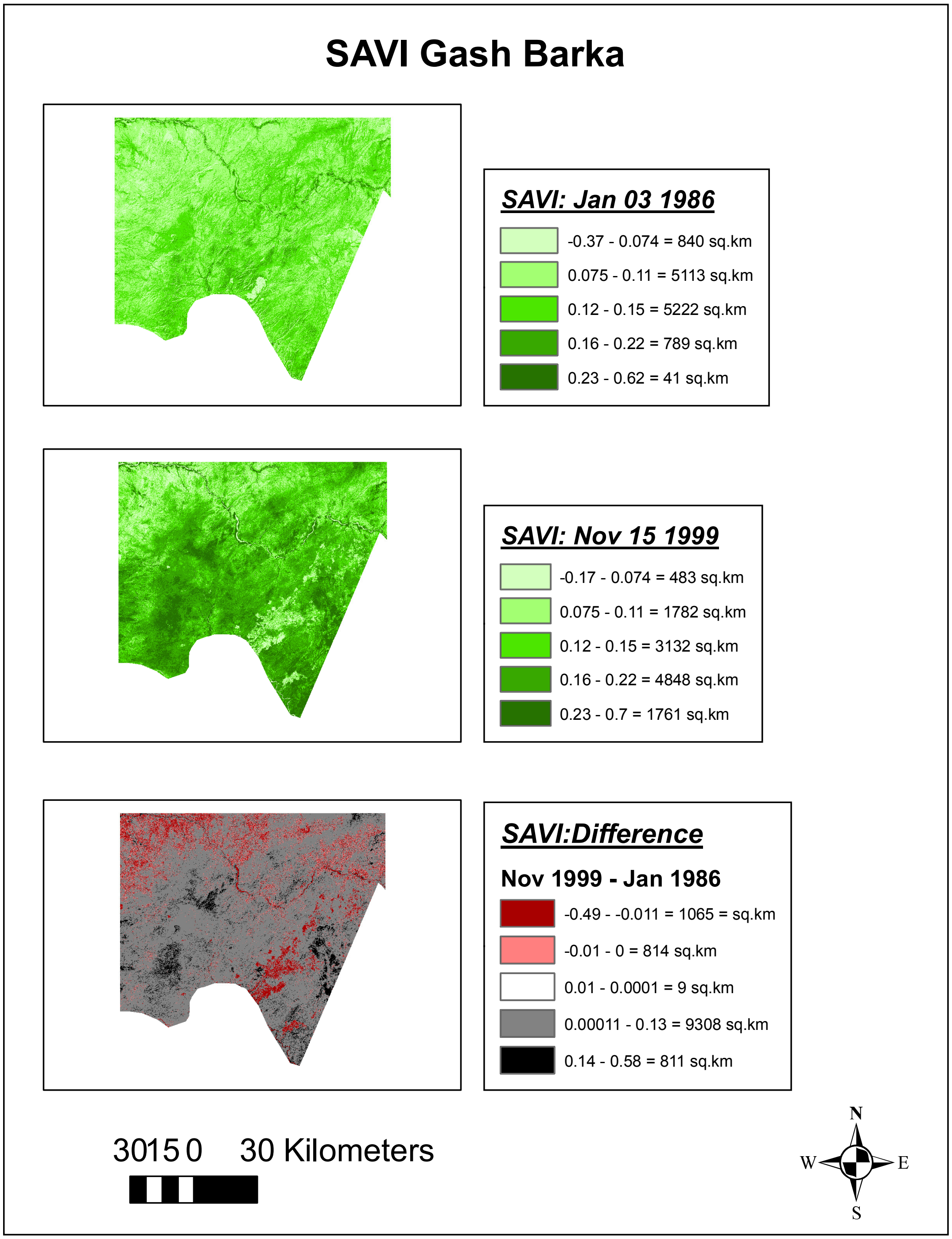

Figure 3.40 SAVI difference analysis analyses in study area 8: Gash Barka (South Western Lowland zone). There was an overall increase in the SAVI value in southern and central parts of the study area, but decrease elsewhere (especially in the northern portions) in 1999 from those of 1986.

Table 3.27 SAVI percent vegetation change in Gash Barka (South Western Lowlands). Note the high decrease in the desert class and the increase in the highland shrub and desert vegetation classes.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this SAVI range in 1986	% of total area in this SAVI range in 1999	% 1999 - % 1986
Desert ((-1) - 0.15)	93	45	-48
Highland shrub (0.16 - 0.22)	7	40	33
Forest (0.23 - 1)	0	15	15
Total	100	100	

The mean SAVI values obtained for January 3, 1986, and November 15, 1999, were 0.12 and 0.17, respectively. Standard deviations were 0.03 and 0.06, respectively. The coefficients of variability were 0.25 and 0.35, respectively, indicating that the 1999 SAVI values were slightly more variable among each other than those of 1986. SAVI vegetation values increased on 84% of the study area and decreased on 16% in 1999 from those of 1986 (Figure 3.40). The desert vegetation class decreased by 52 %, while the highland shrub and forest classes increased 5 and 42 times respectively in 1999 compared to the 1984 level (Table 3.27).

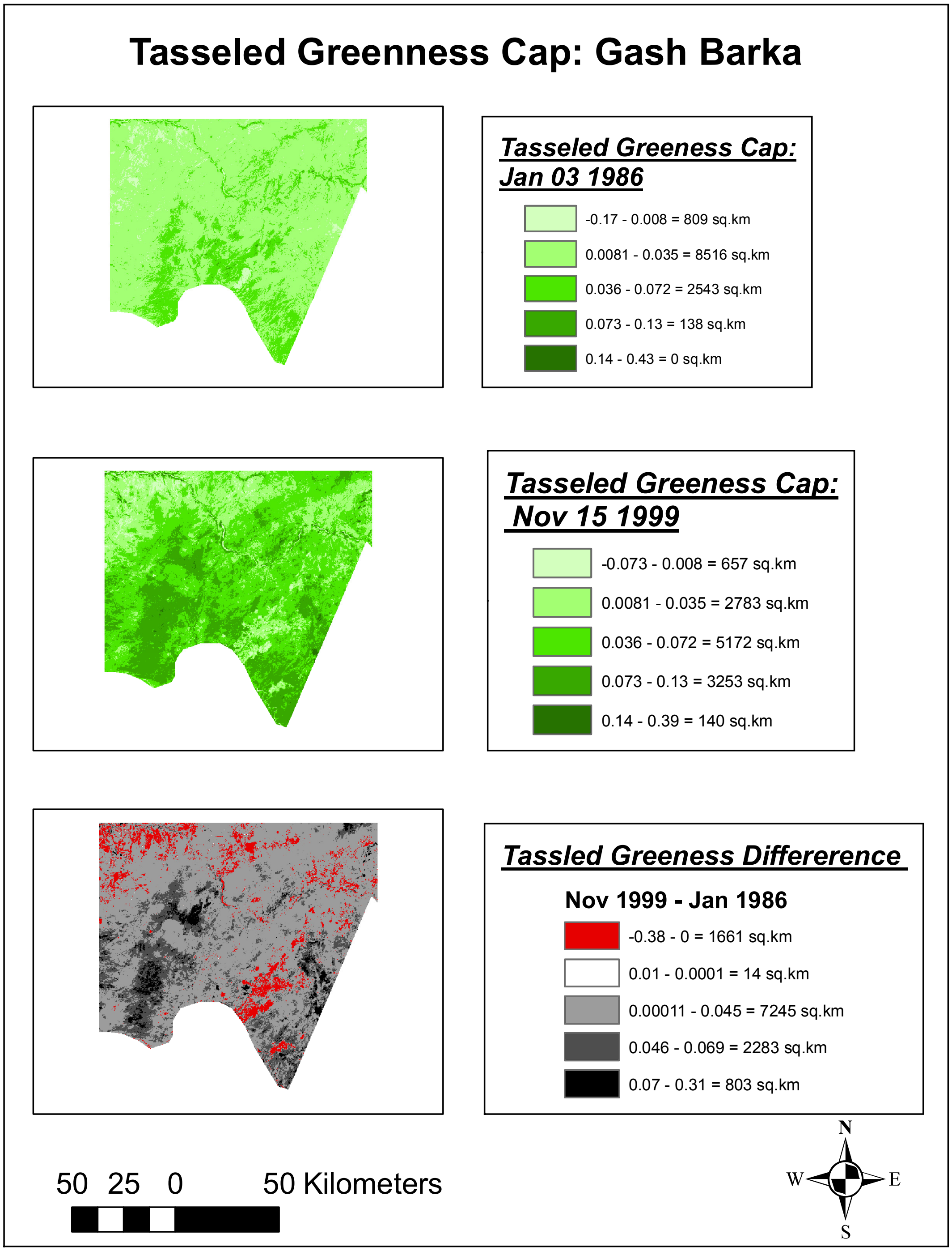

Figure 3.41 Tasseled Greenness difference analysis analyses in study area 8: Gash Barka (South Western Lowland zone). There was an overall increase in the Tasseled Greenness value in overall the study area in 1999 from those of 1986 except for some isolated portions in the North and central south parts of the study area.

Table 3.28 Tasseled Greenness percent vegetation change in Gash Barka (Western Lowlands). Note the high decrease in desert class and the increase in the highland shrub and forest classes.

	Percent in Vegetation		
Classification based on Table 2.2	% of total area in this Tasseled Greenness range in 1986	% of total area in this TC Greenness range in 1999	% 1999 - % 1986
Desert ((-1) - 0.035)	78	29	-49
Highland shrub (0.036 - 0.072)	22	70	48
Forest (0.14 - 1)	0	1	1
	100	100	

The mean Tasseled Greenness value obtained for January 3, 1986, and November 15, 1999, were 0.02 and 0.05, respectively. Standard deviations were 0.01 and 0.03, respectively. The coefficients of variability were 0.50 and 0.60, respectively, indicating that the 1999 Tasseled Greenness values were slightly more variable among each other than those of 1986. Tasseled Greenness values increased on 86% of the study area and decreased on 14% in 1999 from those of 1986 (Figure 3.41). The desert vegetation class decreased by 63%, while the highland shrub and forest classes increased 2.14 and 1.17 times respectively in 1999 compared to the 1984 level (Table 3.28).

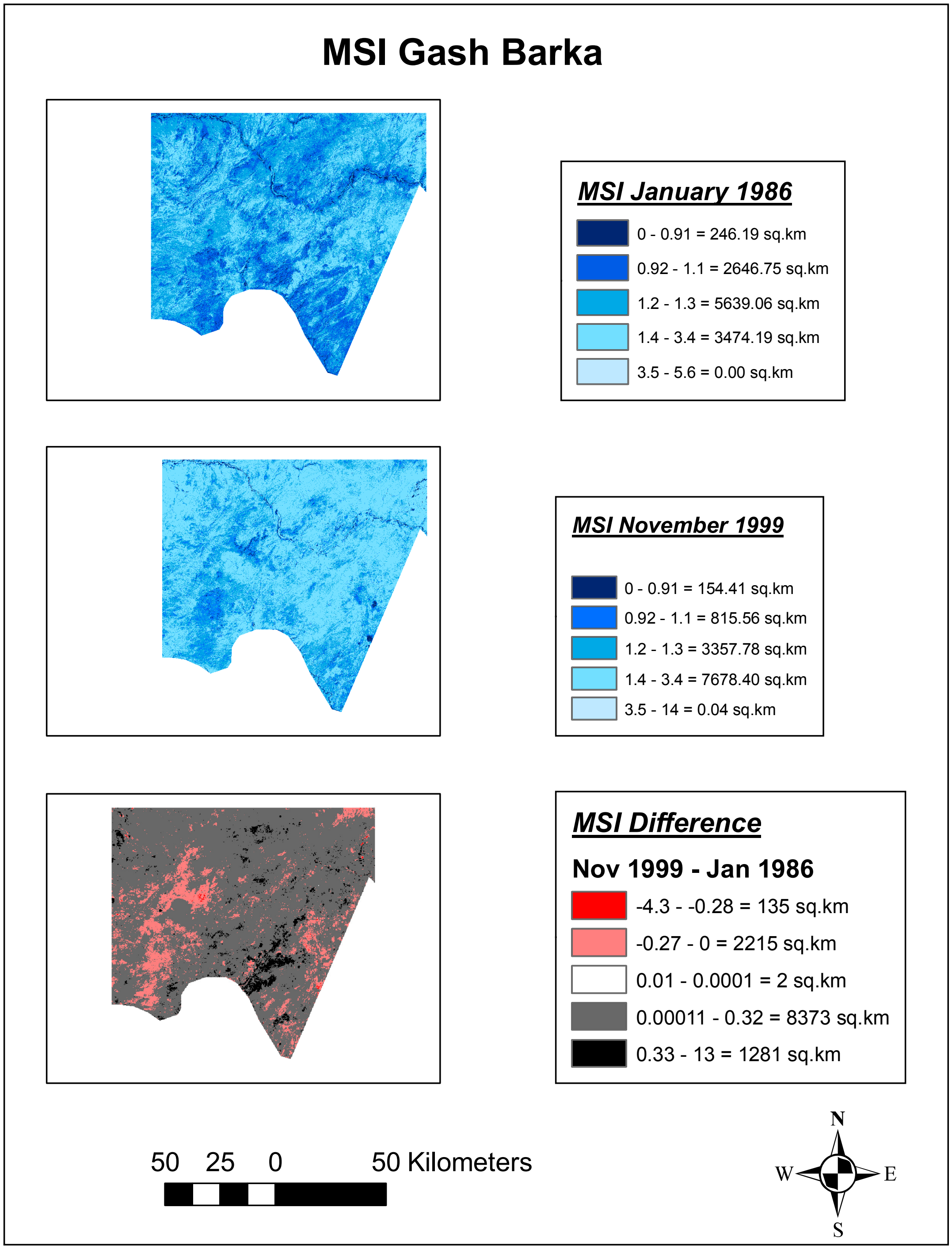

Figure 3.42 MSI difference analysis analyses in study area 8: Gash Barka (South Western Lowland zone). Generally, there was an overall increase in the MSI value in overall the study area in 1999 from those of 1986, except for some parts in the eastern and southwestern portions of the study area.

There was dissimilarity in the results obtained by the MSI and TC Wetness in study area 8. MSI values decreased on 80% (Figure 3.42) of the study area, while TC Wetness values increased on 87% (Figure 3.43). The increase in TC Wetness value corresponded well with the general increase in vegetation values as portrayed by the three vegetation indices. However, the decrease in moisture stress (MSI) did not.

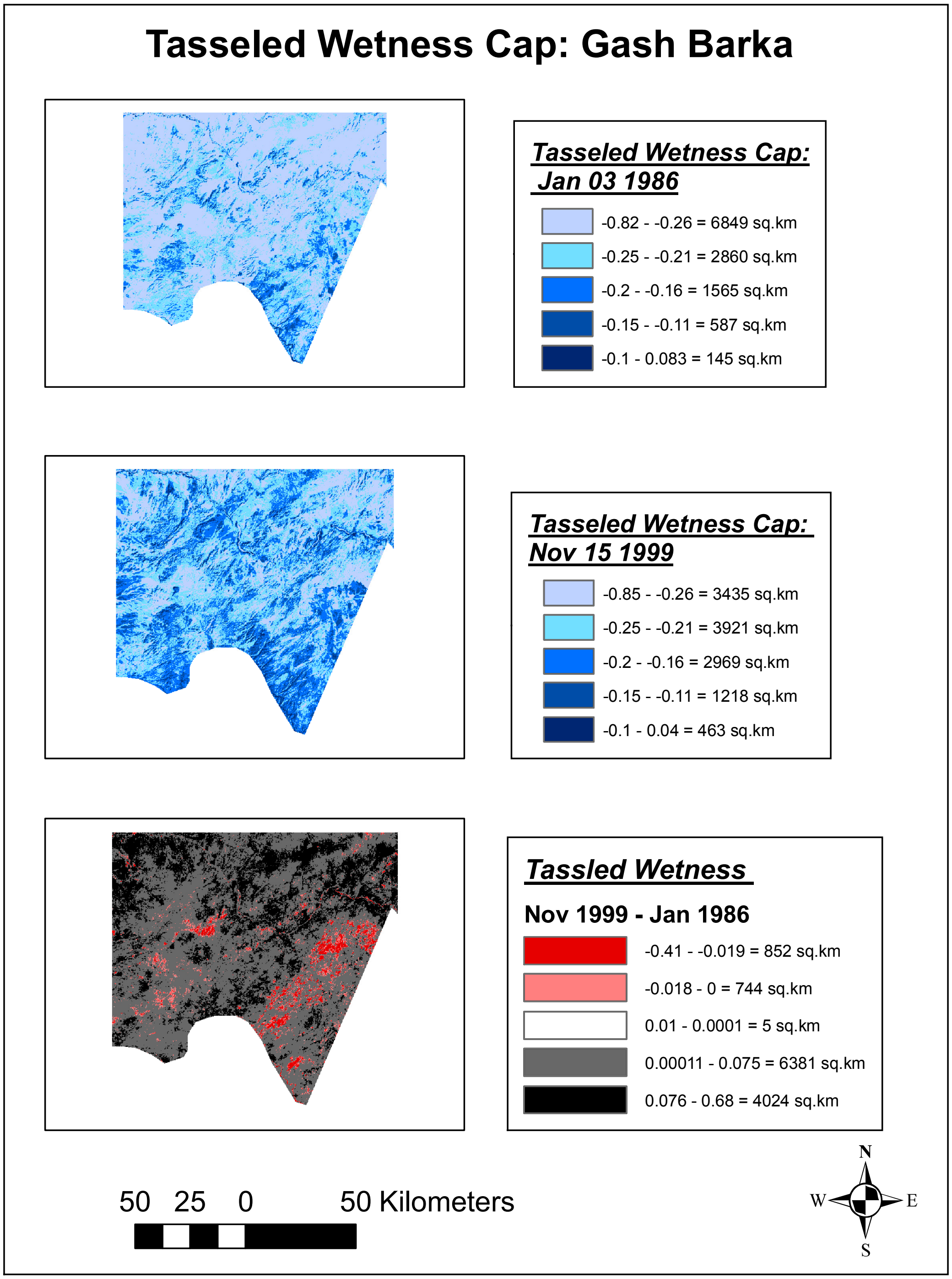

Figure 3.43 TC Wetness difference analysis analyses in study area 8: Gash Barka (South Western Lowland zone). There was an overall increase in the TC Wetness values in overall the study area in 1999 from those of 1986, except for some portions in the southwestern parts of the study area.

3.3 Statistical Analyses for Vegetation Indices Methodologies

Several methods were available for determining whether there was a significant difference between the three vegetation indices. Visual comparisons and comparisons of vegetation change percentages between the eight paired datasets were used in this study. A statistical test, ANOVA, was used to supplement the qualitative observations. These methods were not affected by the spatial extent of analysis, which was conducted at small, and whole study area scale. In section 3.1 (change detection), the vegetation change percentages were described for each study area. In this section, the analysis will be presented in two ways, at a small scale and at the scale of the whole study area. ANOVA (Tukey's method) was used to analyze whether there were differences among the results of the three vegetation indices.

3.3.1 Analysis at a Small Scale

Two sets of thirty two separate samples were chosen from study area 1, which consists of three agro-ecological zones (coastal, eastern escarpment and central highland zones). Each point sample consists of 900m^2 area (30m by 30m). The two separated samples were collected from the coastal plains and escarpment regions, respectively. These areas were chosen because they represented two different ecological zones with different climates, topography and vegetation abundance. The eastern escarpment area represented the area with the highest vegetation coverage, while the coastal plains had the lowest vegetation coverage in Eritrea.

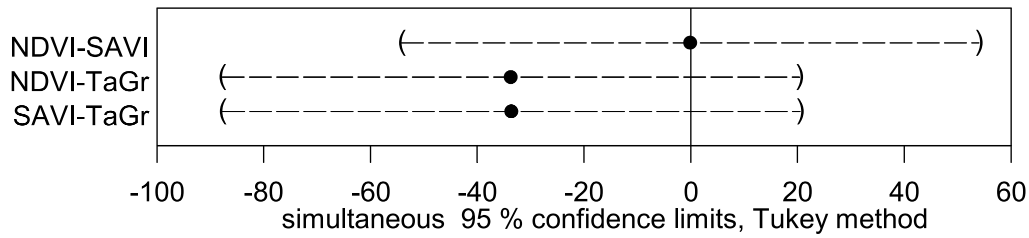

Figure 3.44 Eastern Escarpment: Small Scale ANOVA (Tukey) comparison among NDVI, SAVI, and TC Greenness (TaGr). There is no significant difference among the three indices (n = 32).

For the Eastern escarpment, the ANOVA analysis (Overlapping 95% confidence intervals) indicate a lack of significant difference between the true mean of the vegetation values in NDVI, SAVI, and TC Greenness indices being compared (Figure 3.44).

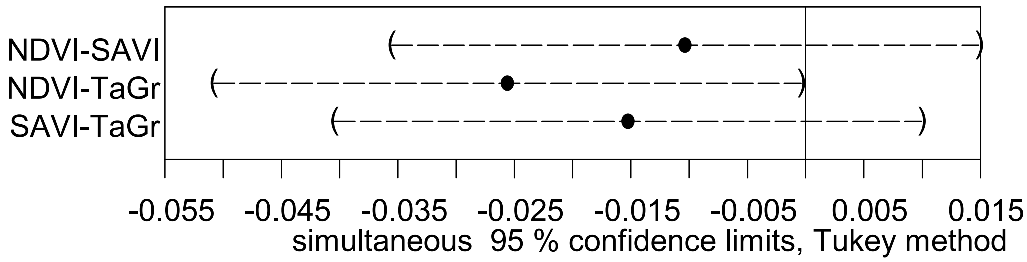

Figure 3.45 Coastal Plains: Small Scale ANOVA (Tukey) comparison among NDVI, SAVI, and TC Greenness (TaGr). There is no significant difference between NDVI and SAVI and between SAVI and TC Greenness, but there was a significant difference between NDVI and Tasseled Greenness (n = 32).

The samples taken from the coastal area showed that there was no statistically (the 95% confidence intervals from the ANOVA analysis) significant difference in the mean vegetation values between SAVI and the other two indices (Fig 3.45). However, there was a statistically significant difference between NDVI and the TC Greenness mean vegetation values at the small scale in the coastal plains.

3.3.2 Analysis at the Full Study Area Level

Analyzing whether there is a difference among the three vegetation indices at the whole study area gives a more reliable result than at a small scale. This is because there are relatively more samples which represent the population.

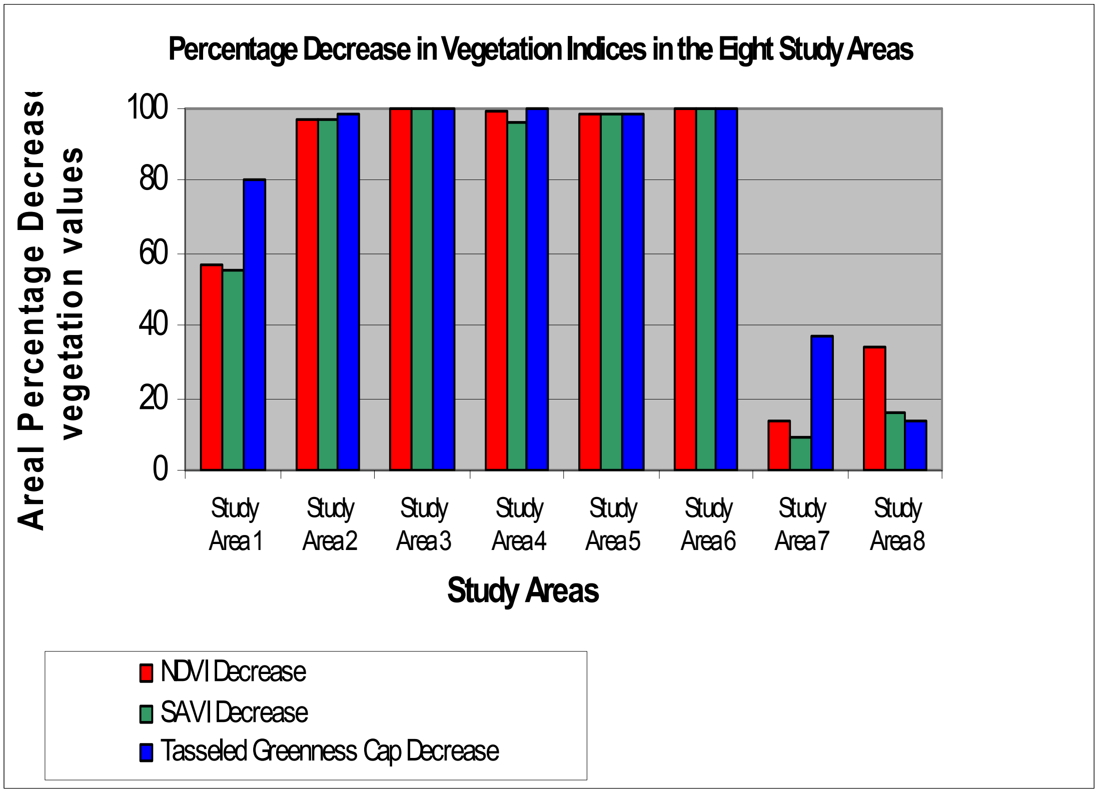

Figure 3.46 Comparison of the percentages of vegetation decrease among the three vegetation indices across the eight study areas. Visually, there was no noticeable difference among the indices in study areas 3, 5, 6, and 7. There was a slightly noticeable difference among the indices in study areas 2 and 4, while there was a highly noticeable difference among the indices in study areas 1 and 8.

Visually, in study area 1 (Highland, Eastern Escarpment and Coast) NDVI and SAVI produced similar values, which both differed from the TC Greenness (Fig 3.46). The almost 100% decrease in vegetation in study areas 2, 3, and 5 was due to the fact that the most recent data sets (2000 and 2002) had vegetation (NDVI, SAVI, and Tasseled Greenness) values below the lowest vegetation values in the earlier data sets (1986 and 1984).

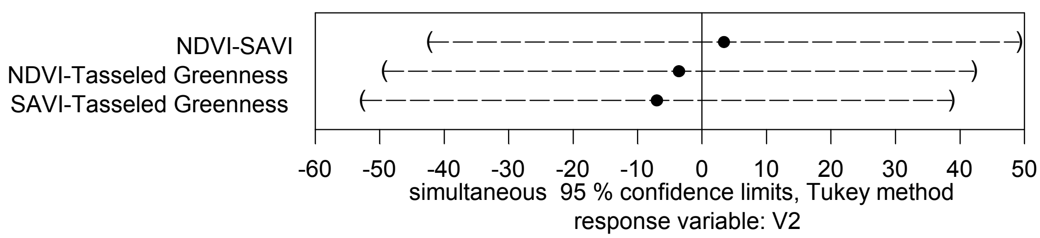

Figure 3.47 All study areas: Full study area level ANOVA (Tukey) comparison among NDVI, SAVI, and TC Greenness (TaGr). There is no significant difference among the three indices.

ANOVA (Tukey) analysis showed that here was no significant difference among the three indices when considering the eight study areas as one (Figure 3.47). It also showed that there was more similarity between NDVI and TC Greenness than between NDVI and SAVI, and also between SAVI and TC Greenness.

4 DISCUSSION

In mapping vegetation change, analyzing whether there are differences among vegetation indices, and also classification of vegetation biomes using Landsat TM and ETM+ in Eritrea from 1984, 1985, and 1986 to those of 1999, 2000, and 2002, several factors seemed to play a role. Spatial and temporal variability was more useful for understanding change than, for example, using the mean value.

4.1 Classification of vegetation

The three vegetation indices showed differences in the overall classification of vegetation areas. A certain degree of subjectivity was used in classifying the study areas into desert, highland, and forest areas. It is possible that these classifications could have been conducted in a less subjective manner with some additional data or ground truthing. The three vegetation indices used in this research do not differentiate between vegetation species. The indices are based on the spectral signature of healthy, photosynthetically active plant leaves. Species could only have been identified using ground data (for example, using GPS to record plant species and locations) or with a spectroradiometer. Without the use of such data, it is possible that some biomes were incorrectly classified, such as seasonal grasses being classified as forested areas. However, the classification seemed reliable as forest areas, shrub areas, and desert areas fit with the experiences of the author as well as with previous studies.

4.2 Mapping Vegetation Change

In study areas 1 to 6, NDVI, SAVI, and TC Greenness showed that there was an overall decrease in vegetation values in 2000 and 2002 from those of the 1984, 1985, and 1986. In study areas 7, and 8, the three vegetation indices showed an increase in vegetation values. The change in vegetation values may be explained mostly by precipitation (rainfall) levels. Rainfall data were obtained from the USGS (2000), Meteorological Services of Eritrea (2004) and personal contacts. Since monthly or daily rainfall data were not available the Moisture Stress Index (MSI) and TC Wetness, along with the available annual rainfall data were used to explain the effect of precipitation on vegetation change. Besides precipitation, other factors such as war, drought, topography, difference in acquisition dates of the Landsat TM and ETM+ images, presence of rivers, and temperature (solar irradiance) also may have had an effect.

Table 4.1 Precipitation (rainfall) data per year per study areas (Source: Meteorological Services of Eritrea 2004).

	Agro ecological zone	Precipitation in millimeter per year		Proxy data from
		1984, 1986 and 1986 data	1999, 2000, and 2002 data	
Study area 1	Coastal zone	45.3mm (1984)	192.6mm (2000)	Asmara
	Eastern escarpment	Not available	Not available	
	Central Highlands	450mm (1984)	543mm (2000)	Massawa
Study area 2	Coastal zone	239.2mm (1986)	3.4mm (2000) and 36.3mm (2002)	Assab
Study area 3	Coastal zone	239.2mm (1986)	3.4mm (2000) and 36.3mm (2002)	Assab
Study area 4	Coastal zone	239.2mm (1986)	3.4mm (2000) and 36.3mm (2002)	Assab
Study area 5	Coastal zone	192.6mm (1984)	45.3mm (2000)	Massawa
Study area 6	North Western Lowlands	Not available	Not available	
Study area 7	Central Highlands and Western Lowlands	450.80mm (1984)	359.8mm (1999)	Asmara
Study area 8	Southwestern Lowland	Not available	Not available	

In study area 1 (Highland, Eastern Escarpment, and Coastal), the decrease in vegetation values may have been due to the decrease in precipitation from 1984 to 2000 (Table 4.1). The data sets for study area 1 were from Nov 22, 1984 and January 27, 2000. Since monthly data for 1984 were available but not for 2000, only annual cumulative rainfall values were used for analysis. Data from Asmara and Massawa were used as proxy data to explain precipitation levels in the highland and coastal zones. Annual cumulative rainfall values were 450 mm and 543 mm for 1984 and 2000, respectively, for the highland areas (Asmara). For the coastal lowland areas, the cumulative rainfall was 45.3 mm and 192.6 mm for the 1984 and 2000, respectively (Massawa). The higher annual precipitation level in 2000 seems to contradict the decrease in vegetation in the coastal lowland areas. One possible explanation for this phenomenon is that, unlike in the highland areas, rainfall is not well distributed in the coastal areas. Thus, during the acquisition time of the Landsat ETM+ image for the 2000 data, there might not have been rainy periods. This problem could have been easily solved if there were sufficient information regarding monthly rainfall data. No rainfall data were available for the analysis of rainfall in the Eastern escarpment area. The lower amount of rainfall is compounded by the increase in the MSI value and the decrease in TC Wetness Values in 2000 from those of 1984 (Figures 3.7 and 3.8).

Precipitation levels seemed to have also been the major factor in the decrease in vegetation values as seen in study areas 2, 3, 4, and 5 (Denkalia, South Denkalia, Central Denkalia, and North east Sahel). The total amount of rainfall for 2000 was only 3.4mm, while it was 239.2 mm for 1986 (the Assab rainfall data is used as a proxy for the study areas 2, 3, and 4) and it was 36.3 mm in 2002 (Table 4.1). The rainfall pattern for study area 5 is slightly different from the others as the area is located farther north, thus rainfall data from Massawa were used as proxy data. The total annual rainfall amounts for Massawa were 192.6mm and 45.3mm for 1984 and 2000, respectively. The precipitation values seem to correspond well with the spatial increase in moisture stress and the decrease in wetness as seen in the MSI and TC Wetness values respectively (Figures 3.12, 3.17, 3.22, 3.27 and Figures 3.13, 3.18, 3.23, 3.28). The increase in vegetation indices just on the coastal part (eastward edge) of these study areas may be due to presence of rivers, moisture gusts coming from the Red Sea and changes in settlement coastal farming.

There were no available data to be used as a proxy for the 1986 rainfall data, so only the visuals of MSI and TC Wetness data were used in this case. Both of these indices show that there was an increase in MSI and decrease in TC Wetness values in 2000 from those of 1986, which coincides well with the decrease in vegetation shown by the three vegetation indices (Figures 3.32 and 3.33).

Both study areas 7 (Southern Highlands) and 8 (Gash Barka) showed an increase in vegetation values in 1999 from those of 1984 and 1986. Rainfall from Asmara was used as a proxy for study area 7 (November 22, 1984 and November 25, 1999 datasets). The total annual rainfall was 450.8mm for 1984 and 359.8mm for 1999. The higher annual rainfall in 1984 relative to 1999 did not explain the increase in vegetation in 1999. However, the decrease in moisture stress (MSI) and also increase in TC wetness in 1999 relative to 1986 did explain the increase in vegetation values in 1999 (Figures 3.34, and 3.35). Rainfall data were not available for 1986 for study area 8, and thus only the MSI and TC Wetness were used. Both the MSI and TC Wetness values coincide well with the increase in vegetation values shown by the vegetation indices (Figures 3.39, and 3.40). Some plausible explanations on why the annual rainfall was not coinciding with the vegetation indices values (MSI and TC Wetness) in study area 7 are:

- Annual rainfall may not have been the best variable as it might have rained more during the images taken in 1999 but not in 1984. The above idea seemed to be supported well as approximately 241mm and 325mm of the rainfall occurred during the months of July and August for the 1984 and 1999 datasets, respectively (which are the most influential rainy months).
- The Asmara annual proxy rainfall data might not have been a good data source to be used.
- Other factors besides rainfall, such as drought, temperature (solar irradiance), topography, variation in vegetation response, difference in acquisition dates of the Landstat TM and ETM+ images, and war also may have had an effect.

The onset of a drought in 2000 seemed to be one of the main causes for the vegetation values to decrease to levels lower than those of mid-1980 (except in the eastern escarpment zone in study area 1). The mid-eighties were drought years, including 1983 and 1984 in the Sahel with exception of 1986 (Rock 1999). However, there are indications that 1986 was a drought year in Eritrea even though some parts of its lands were part of the Sahel. Although both 1983 and

1984 were drought years, the year 2000 might have been a drier one as Eritrea was entering its 4th year of consecutive drought as of 2004 (Kifle 2003). The increase in vegetation index values in 1999 seemed to coincide with studies done in the Sahelian areas; previous studies indicated a recovery from the Sahelian drought of the mid-1980s (Eklundh and Olsson (2003), Sjöström (2004)).

Another factor that greatly affects the rainfall pattern and thus the vegetation in Eritrea is topographic variability. The increase in vegetation values in study area 1 in the eastern escarpment zone and the decrease in the coastal zone may mainly be attributed to topography effects. NDVI data overlaid on digital elevation data (1km by 1km spatial resolution) show the effect of topography on vegetation patterns (Figure 4.1). The lowest amount of vegetation existed in the coastal areas to the East and the highest was found in the escarpment region (where there was a steep gradient in elevation) due to the orographic rain effect. In Study areas 2, 3, 4, 5 and 6 topography does not seem to be a leading cause in the variability of vegetation or rainfall amount as these areas are flat and show very low variability within the study areas.

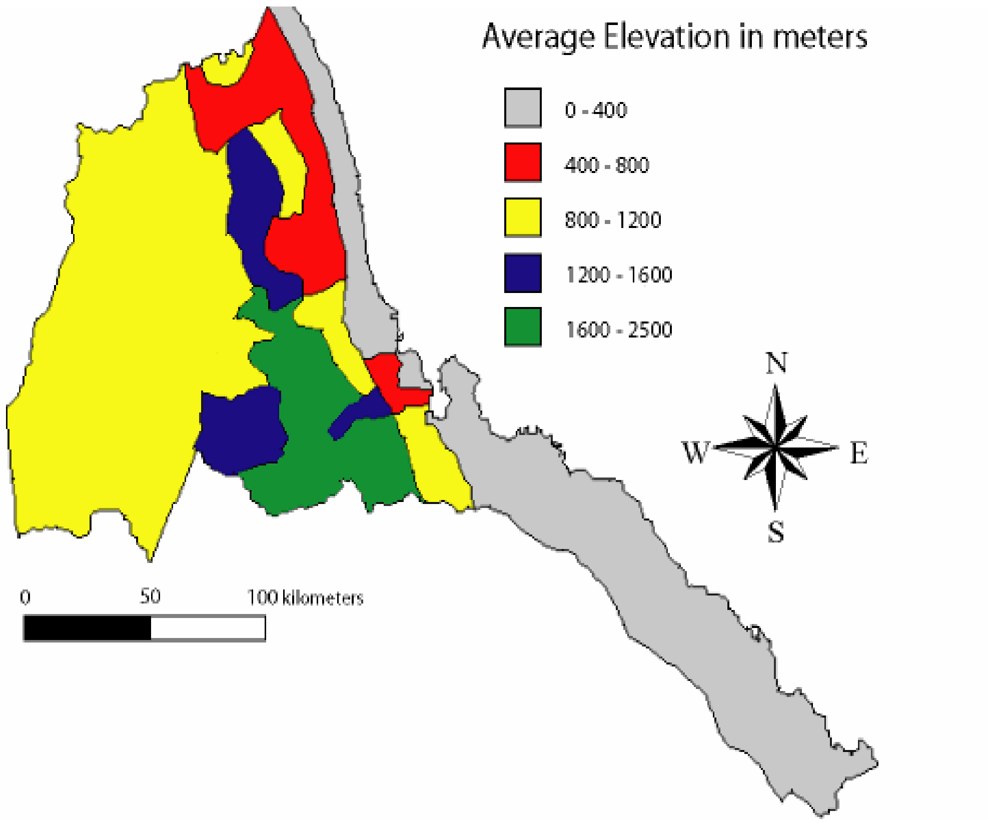

Figure 4.1 Elevation characteristics of Eritrea (adapted from USGS 2004)

Besides topography, the difference in acquisition dates for the pair of Landsat images being compared should be as close to the exact time as possible. But due to the low temporal resolution of Landsat TM and ETM+, the images being compared cannot be perfectly matched. In this paper each pair of images being compared match seasonally. Except for study areas 6 and 7, image dates for all the study areas do not match even to the same month (usually a gap of one or two months). These seasonal differences might produce impressions of long-term vegetation change that are really only seasonal. For example, the November 1984 data would show vegetation index values than those from the January 2000 data in study area 1 and 5 because January is a drier month than November (the rainy season in Eritrea is from July to August). The above seasonal variation in dryness was also the case with the two temporal data sets being compared in study areas 2 (January 1986, and February 2000), 3 (March 1986 and May 2000) and 4 (January 1986 and February 2002).

Another factor having an effect in vegetation change in Eritrea is the river flow system. Rivers in Eritrea might affect the increase and decrease in vegetation by transporting water, helping farmers in irrigating farm areas and flooding river banks. Visual observation in river delta areas showed that all eight study areas (even study areas 7 and 8 which showed an increase in vegetation index values) showed a decline in vegetation index values in 1999, 2000, and 2002 from those of 1984, 1985, and 1986. This phenomenon might be due to several reasons, such as:

- There was a decrease in the annual rainfall in 1999, 2000, and 2002 from those of 1984, 1985, and 1986 (Table 4.1).
- There was a decrease in the main river source areas. The river source areas could have a different precipitation from the proxy areas being used to assess.

Another potentially significant explanation for the decline of vegetation in Eritrea was the war for independence (1961-1991) and the Ethio-Eritrean war (1998-2000). The army uses a lot of fuel wood and trees for their livelihood as well as for the construction of trenches. The relative peace in 1991-1998 was expected to bring higher environmental benefits including increase in vegetation as there were more reforestation programs and more control of the area (regulations on cutting trees) by the government. All of the study areas in this paper were not high intensity war zones during the war for independence (1961-1991) but study areas 7 and 8 were high intensity war zones during the Ethio-Eritrean war (1998-2000). With high army concentrations in these study areas it was expected that there would be a decrease in the vegetation index values in 1999 from those of 1984. However, there was an increase in vegetation values in study areas 7 and 8 in 1999 from those of 1984 and 1986, respectively, despite Eritrea and Ethiopia having fought a bitter border war from 1998-99 in the southern fringes of both study areas. The increase in vegetation in these study areas might be explained by the fact that 1984 was a drought year while 1999 was not as well as by reforestation and soil and water conservation efforts of the Eritrean government that occurred after the nation's independence. Nevertheless, the deforestation rate may have increased substantially by January 2000, as most of the Eritrean army had moved back to the northern part of the study area.

Overall, it can be stated with confidence that the vegetation changes detected were reliable. This is especially true for study areas 1 to 6. Because all the results from the annual rainfall data, all three vegetation indices and moisture indices and the widely published drought occurrence in 2000 seemed to be consistent with the findings. Some consequences of the overall decrease in vegetation indices values could be decrease in soil moisture level, increase in soil erosion, decrease in crop production, and decrease in forage. The results could be used as solid enough to base policy for large scale areas on them especially. However, ground-based data are recommended for small scale areas, and when the cost of research is not an impediment. Some of the policy implications are in reforestation programs, and crop production (agricultural productivity).

4.3 Differences among the three vegetation indices

Generally, there seemed to be no difference in using NDVI, SAVI and TC Greenness. Spatial extent seemed to play a role in the analysis of the differences among the three vegetation indices. Vegetation change percentages were calculated for paired data sets using the entire eight study areas, while 32 samples each from 1984 and 2000 (32 from escarpment zone and 32 from coastal zone) were used from study area 1. There was no difference between the indices when assessed over the full study area (study areas 1 to 8) and in the small scale study in the escarpment. The exception was that the small scale study (32 samples) from the coastal plains zone showed a difference between the NDVI and TC Greenness index. However, this phenomenon could not be extrapolated to all the coastal zone study areas as

ANOVA analysis of vegetation index decrease in 2000 and 2002 from those of those of 1984 and 1986 in study areas 2,3,4, and 5 (which are all exclusively in the coastal agro-ecological zone) showed that there was no difference among the three vegetation indices. The above finding that there was no statistically significant difference among the three vegetation indices seems to contrast with previous research, alleging that especially NDVI is affected seriously by the brightness composition of soils (Huete 1988, Huete 1991, and Schmidt and Karnieli 2001). However, the L value which balances the effect of soil in the SAVI may have had to be adjusted from the 0.5 standard value. Huete (1988) suggests that a higher L value should be used for dry areas. An L value of 0.5 was used in this paper to standardize and compare the indices because the Eritrean landscape has a complex topography with interspersed arid and non-arid lands.

The ANOVA statistics method seemed to agree with the percentage decrease in vegetation index values (Table 3.46). NDVI, SAVI, and TC Greenness produced almost the same magnitude and direction of vegetation change in most of the study areas. The exceptions were in study area 1 and 8. In study area 1, the TC Greenness vegetation change magnitude differed from the SAVI and NDVI. In study area 8, NDVI vegetation change magnitude was noticeably different than that of SAVI and TC Greenness.

A more detailed and ground data-based analysis could probably have solved this inconsistency by looking into the effects of vegetation (type, coverage extent, vertical structure, etc), soil factors (type, and moisture content), and topographic factors (shadow effects, aspect, and elevation). It is probable that if ground truth samples of the study areas were available, the Tasseled Cap transformation would likely have been the more reliable index, in identifying the species, age and structure of vegetation as it was developed to measure crop activities, and thus have a greater capability for identifying details (Kauth and Thomas 1976). Moreover, the Tasseled Cap has a soil factor which is standard and not subjective as the L value in the SAVI equation.

4.4 Limitations

The methods used in this study could be improved in several ways. First, ground-collected vegetation data would have made the analyses more reliable. Second, the dates compared for vegetation change did not match exactly. Only the data used for the study area 7 have the temporal similarity to guarantee a reliable comparison (November 22, 1986 and November 25, 1999). Third, none of the vegetation indices could differentiate plant species. Although the SAVI and the TC Greenness complemented the NDVI by analyzing the effect of soil, none of the indices could distinguish the vegetation species, and the seasonal vegetation could not be differentiated from the permanent vegetation without the availability of ground truth data.

Fourth, the spatial resolution of the data used was 30 meters, meaning that the Landsat TM and ETM+ images could not be used to differentiate the spectral variation of vegetation at higher resolution (for example, 10m). Fifth, the relationship between NDVI and vegetation cover is not linear, and thus the values for percent increase and decrease in vegetation cover could have been inaccurate. For example, a doubling in the NDVI value does not indicate a doubling in the amount of vegetation coverage. Sixth, climate (especially rainfall) may have been the principal controller of vegetation cover as opposed to deforestation. It was hypothesized that deforestation results in lower NDVI values, but grasses or other non-tree vegetation types that are not subject to deforestation may also alter NDVI values, even in the dry season during the months of November to January. Seventh, some of the study areas were in the Eritrean highlands, potentially allowing for topographic relief to cause shading that can hinder the acquisition of NDVI values by affecting the spectral signatures of vegetation. Eighth, spatially and temporally accurate data on rainfall, which is the most important factor required for the analysis of vegetation change, was hard to obtain. The only data obtainable for comparison were from 1984, 1985 and 1986 and from 1999, 2000 and 2002. Monthly (in dekads, which means every 10 days) rainfall data for the earlier set of years were available for only three cities (Asmara, Massawa and Assab), while only yearly rainfall was available for the latter set of years. Thus, only yearly rainfall data were used for the analysis. However, these data were complemented by the TC Wetness index and the MSI.

4.5 Usefulness of data

Mapping vegetation using remote sensing data can be very helpful in making policy decisions. The majority of Eritreans live in rural areas and they are either agriculturalists or pastoralists. The spatial and temporal patterns of vegetation change might shed light on the factors affecting vegetation changes. The effect of these factors (for example, drought) in the past could suggest trends about where and when such consequences might occur in the future. Hence, the mapping of vegetation change could allow for the anticipation of future events, and could therefore aid in the development of future strategies (for example, drought emergency relief programs). Some of the programs developed by the Ministry of Agriculture are to adopt crops which are more suited to drought stricken lands. One of the famous examples is the SASAKAWA Global 2000 project, which suggested short crops requiring a small amount of water (Ghebru, and Kohler 1999). The results from this paper could serve as an indicator on the reforestation and soil and water conservation (reforestation) programs in Eritrea. It is an opinion that most reforestation programs failed in Eritrea because tree seedlings were planted in naturally dry areas where moisture availability and vegetation are low. Thus focusing on areas that, in this study, showed an increase in vegetation and moisture could be given priorities in reforestation programs. Millions of trees are planted during every rainy season. Some of the most common indigenous and exotic species are *Juniperus procera*, *Olea Africana*, *Hyphaene thebaica*, *Tamarix aphylla* and *Eucalyptus cladocalyx*, respectively (Negassi et al 2000 and Emerton and Asrat 1998).

5 CONCLUSION

The three objectives of this paper were: 1) to classify vegetation in eight study areas into desert, highland shrub, and forest using Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and TC Greenness, 2) to map vegetation changes using the above three vegetation indices and explain the causes and consequences of vegetation change, and also 3) to analyze whether there is any difference among the three vegetation indices in mapping vegetation change.

The classification fitted the expectation that there would be deserts in the coastal areas (study areas 2, 3, 4, 5 and 6), highland shrubs in the central highlands and forests in study area 7 (Gash-Southwest Eritrea), study area 8 (Southern Highlands) and in some portions of study area 1 (Eastern Escarpment-Eastern Eritrea). The classification of vegetation was very similar to that of previous studies in Eritrea.

NDVI, SAVI, and TC Greenness values were higher in 1999 from those of 1984 and 1986 study areas 7 (southern highlands) and 8 (Gash Barka). Some of the reasons for the increase are: 1) the year 1984 was a drought year, 2) although there was a higher annual rainfall in 1984 than in 1999, the rainfall distribution might have been different in that it might have rained more during the periods when the image was acquired in 1999 but not in 1984 and 1986, 3). The increase in vegetation in 1999 could also be attributed to the relative peace and reforestation programs that occurred between 1993 and 1997. However, it was an expectation that there might be a decrease in vegetation in 1999 due to the negative effect of war between Ethiopia and Eritrea from 1998 to 1999. Contrary to the 1999, the three vegetation indices showed a decline in vegetation values in 2000 and 2002 from those of 1984, 1985, and 1986 in six of the study areas. The main reasons for the declines in the 2000 and 2002 were lower amounts of annual rainfall relative to the mid-1980s data and the beginning of a four-year drought (2000 up until 2004). Recently in 2005, there was a higher amount of rainfall which seemed to end the drought.

Visually, six of the eight study areas showed no difference among the three vegetation indices (SAVI, NDVI, and TC Greenness). Study area 1 showed that the TC Greenness result was different than NDVI and SAVI, while study area 8 showed that the NDVI result was different than the SAVI and TC Greenness.

There was no statistically significant difference in using the NDVI, SAVI, and the TC Greenness index when the assessment was conducted with the eight study areas combined (large scale). Out of the two small scale studies conducted, one showed that there was a statistically significant difference between NDVI and TC Greenness, while the other one showed no difference among the three vegetation indices.

The NDVI, SAVI and the TC Greenness vegetation indices can be very useful in the analysis of vegetation cover, especially when ground-based data are not available. Using such indices could be especially beneficial when obtaining ground-based data is expensive or dangerous. Future studies that could be done related to this paper are: 1) collect ground data to ascertain the results of this paper and 2) other satellite sensors such as the AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) could be used to ascertain the results obtained from the study areas in this paper, as these sensors have a higher temporal resolution but lower spatial resolution than the Landsat data used in this thesis.

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