Assessment of Desert Locust Outbreaks in Sudan Using GIS and remote sensing technologies

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DECLARATION

I, Hussien Osman Abaker, declare that the following dissertation is entirely my own work and has not been submitted, in whole or in part, for any award to any other academic institution.

Signed……………………………………………………..

Date…………………………………………

DEDICATION

This dissertation is dedicated to:

the soul of my late Mother,

my father,

my uncle Siddig Abaker,

And

my Wife Noha Mohammed Easa

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ABESTRACT

Desert Locust (Schistocerca gregaria, Forskal) is considered to be the most serious pests that cause a devastated damage to the crops and the other agricultural products during their invasions. More information is needed about the underlying systems and rainfall triggers that promote widespread vegetation and locust population growth leading to upsurge and possible plagues. The aim of this study is to carry a detailed study to Desert Locust plague occurred in Sudan in 2003 and continued up to 2004. The objectives achieved by using GIS and Remote sensing tools to find clear answers for such question like where and when the initiation of the outbreak started, why and how the outbreak developed, what factors that led to the development and continuation of that plague. Desert Locust historical data used in the study was collected by survey teams from Plant Protection Directorate (PPD), Sudan, during years 2003, 2004 and 2005. Also satellite images of MODIS EVI (Moderate-Resolution Imaging Spectra-radiometer Enhanced Vegetation Index) 16-day data with a spatial resolution of 1 km and, 10 days accumulated rainfall estimates were also used in this study. ERDAS IMAGINE and ARC GIS 9.3.3 were used for data processing. Spectral profiles were extracted from the satellite images to quantify vegetation amount and estimate the total rainfall amount for each season separately. Binary logistic regression analysis and t-test analysis performed in this study using Minitab software. Binary logistic regression analysis was looking for the relationships between the categorical variables, which were the presence and the absence of the Desert locust and the predictive variables considered as the maximum, minimum EVI values and Total rainfall. T– test was used for comparing Maximum EVI value and total rainfall between the years, and that for examining which of the years appeared to accommodate much resources, that might strongly influenced the development of Desert Locust. It was found that in the result every year during the study period had different infestation pattern and distribution trend along the breeding areas in both winter and summer. But most of locust initiation and development was strongly related to the amount of rainfall and abundance of green vegetation, beside other factors. Recommendations were obtained according to the results, to supported improving Desert Locust monitoring and forecasting operations, and that contribute largely in minimizing the risk of the locust in Sudan, as well as in the region.

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Abbreviations

APLC	Australian Plague Locust Commission
AVHRR	Advanced Very High Resolution Radiometer
BoM	Buearu of Meteorology
CMORPH	
DL	Desert Locust
DLIS	Desert Locust Information Section
DSS	Decision Support System
ECLO	Emergency centre for Locust Operations
ECMWF	European Centre for Medium-range Weather Forecasts
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organisation of the United Nations
GIS	Geographic Information System(s)
GPS	Global Positioning System
IRI	International Research Institute for Climate and Society, Columbia University.
MoA	Ministry of Agriculture
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
PPD	Plant Protection Directorate
RAMSES	Reconnaissance and Management System of the Environment of *Schistocerc*
REF	Rainfall Estimate
SPOT	Système Probatoire d'Observation de la Terre
SWARMS	Schistocerca Warning and Management System

Chapter One

Chapter 1

Introduction

1.1. Background of the study

The desert locust (Schistocerca gregaria, Forskl) is considered to be one of the most serious pests to cause a devastating amount of damage to the crops and the other agricultural products during their invasions. It has the largest distribution area, which extends from West Africa through the Middle East to East Asia (Abdella, 2004). The desert locust lives in arid and semi- arid desert habitats, living solitarily when the climatic conditions are not suitable for breeding. During plagues, the locust population increases in size and invades vast areas and more than 60 countries in Africa and Asia are affected at different degrees of infestation during the plague development (Steedman, 1990), which normally occurs due to consecutive generations of successful breeding followed by favourable sequences of heavy and widespread rainfall (Dutta, et al.2008). The recession and invasion areas (See the maps Fig. 1) are characterised by seasonal rainfall, averaging between 80 and 400 mm annually, which can vary dramatically from year to year with annual rainfall being up to 70% above or below average (Magor, 1994). Sudan has two desert locust breeding sites, including the summer breeding zone which covers large areas dominated by the plain sandy dunes of Western and Northern parts of Sudan (Darfur, Kodofan and River Nile and The Northern states), where the rainy season normally starts in June and ends in October. The other site is the winter breeding zone, which extends from the southern borders of Sudan and Eritrea and north up to Sudan and the Egyptian borders, where the rain starts from November to March.

Locust plagues are initiated by uncontrolled local outbreaks that develop in the frontline countries, which extend from Mauritania in Africa to India (Cressman, 2008). It is uncertain whether the plagues start from a concentration of scattered locusts followed by successful breeding and grangerization or from the carry-over of swarms during recessions. However, it is known that locusts move seasonally between complementary breeding zones during recessions (Van Huis, et al. 2006). So far, successful breeding requires a high degree of spatiotemporal coincidence between the adult locusts and rain, and this is normally achieved by downwind migration that takes locusts towards areas of horizontal wind convergence where there is rainfall. Breeding areas often spread over vast areas, which are lacking in good roads and are sometimes inaccessible because they are insecure or coincide with areas of civil conflict (Pekel, et al. 2010).

1.2. Desert Locust Plague Initiations and Monitoring

International and national bodies concerning desert locusts worldwide have adopted many strategies to minimize the risks of insects, and so far, intensive research has been conducted. Showler (1997) outlines three broad strategic approaches based on intervention timing. The initial approach is a preventative strategy. It mainly depends on preforming locust control before the onset of gregarious behaviour and when locusts have amassed in small patches for several square metres in breeding areas, or before that if phase transformation can be anticipated (Showler, 2002). The second is a pro-active strategy; it entails intervention against localized outbreaks to prevent them from reaching plague status, and it also relies on early detection of bands and swarms, preferably in breeding areas, and pre-positioning of campaign resources. In addition, the last one is a reactive strategy; it is a default circumstance rather than a deliberate strategy because the interventions occur mostly after the plague status is reached. Magor, et al., (2008) state that, the preventive control strategy of treating bands and swarms, as soon as they formed in outbreak areas influenced locust management throughout the world and was well suited to species that have distinct outbreak areas of small to moderate size. As well as major achievement of preventive control of the desert locust since 1965 no plague has reached the full geographical extent of earlier ones, and it was concluded that the potential benefit of early intervention is that locust numbers may be kept below plague levels during the brief periods of exceptional weather that favour maximum population growth. Sword et al, (2010) state that, over the past 50 years the desert locust preventive control programme achieved the required objectives, by preventing swarms invading the majority of large cultivated areas. Furthermore, Magor et al. (2008) suggested that it was likely an earlier intervention strategy should further reduce the duration and extent of plagues of this species and could entirely prevent some of them.

Early detection of changes in the desert locust dynamic is a critical issue in preventive control strategy; therefore, many attempts have been undertaken to facilitate survey operation towards areas most likely to be infested by locust population that could transform their phases. While most early research on desert locust population dynamics are carried out to predict the development and movement of swarms during plagues, the emphasis has now changed to identifying the sequences of rainfall and vegetation change that lead to the growth of existing locust populations and the possible initiation of upsurges and plagues (Rosenberg, 2000).Since 1978, FAO has operated the Desert Locust Information Service (DLIS) in Rome on a continual basis for monitoring the weather, ecological conditions, and desert locust infestations (Cressman and Hodson, 2008). Locust populations and environmental conditions in affected areas are monitored using reports from national locust survey teams and meteorological and satellite data; these data are entered into a model that forecasts potential locust migrations and breeding (Cressman, 1996). Since 1996, SWARMS (Schistocerca Warning and Management System) has been used at FAO DLIS in Rome on a daily basis to manage and analyse environmental and locust data. Smaller and simpler GIS, RAMSES (Reconnaissance And Management System of the Environment of Schistocerca), were developed for countries, which were introduced in 2000 (Cressman, 2008). RAMSES was designed to focus more on medium-and short-term forecasts for the immediate region. It allows the current locust and environmental situation compared visually to the previous month's situation, or to comparable months in former years and to historical analogues that show how and why previous locust events developed (Pedgley, 1981). Bernardi (2001) mentioned that the ability to manage large amounts of geographically referenced data makes GIS technology integrate spatial and other related information (attributes) within a single computer system and allows access to attribute information by geographic location. Moreover, GIS software provides the functions and tools needed to store, analyse, and display geographic information. In the past, much of a forecaster's time spent manually re-plotting all the data on different scales to produce an overview of the pest and environmental situation for a defined period. The advantage of GIS-based technology is that it is designed to enable the different data layers to be displayed simultaneously, thereby releasing the forecaster from routine re-plotting tasks to focus on interpretation and assessment and the building-up of databases for historical analogues (Cressman, 1998).

Remote sensing techniques can greatly facilitate monitoring locust population dynamics over a large geographic scale. The application of such techniques has two main objectives:

(1) Early warning, which forecast the regions mostly like to be infested by locusts

(2) Damage assessment including identification of the extent and severity of damage, which since the late 1970s have been used to detect potential outbreak areas of the desert locust Schistocerca gregaria (Forskal) in Southeast Asia and northwest Africa (Pedgley, 1973; Hielkema et al., 1986; Tucker et al., 1985; Ji et al, 2004). Satellite sensors, meteorological

numerical models, and rainfall algorithms have improved since the late 1990s, and new products developed to estimate rainfall on a local, regional, or global level. Since 2006, FAO DLIS had been using decadal rainfall estimate maps. They were produced by Columbia University, International Research Institute for Climate and Society (IRI) and can be displayed and downloaded for free from the Internet and imported easily into any GIS such as SWARMS or RAMSES. It has been found that they are a much better estimate of rainfall than data from the relatively few national meteorological stations in the desert locust breeding areas (Cressman, 2008). Numbers of remote sensing images are used for detecting green vegetation of desert locust distribution areas. NDVI, at 1.1km resolution has been used operationally to monitor desert locust environments, at the Food and Agricultural Organisation (FAO) since the mid-1980s and, then in the mid-1990s, 1 km NOAA-AVHRR resolution imagery became available, but this was replaced in about 2000 by 1 km resolution SPOT imagery because the SPOT sensor was specifically designed for vegetation monitoring. However, this imagery has been superseded by 250-metre resolution MODIS imagery since 2006. Currently, innovative multi-temporal and multi-spectral image analysis methods are being developed for detecting vegetation in arid and semi-arid areas. It is a complete automatic processing chain designed to combine the daily observations from MODIS (Aqua & Terra) and SPOT VEGETATION, and it provides operationally and in almost real time, a user-friendly vegetation dynamic map updated every 10 days over the whole desert locust area at 250 m resolution (partially based on MIR 500 m) (Pekel, et al., 2010).

1.3. Aims and Objectives of the Study

The aim of this research is to carry out a detailed study of desert locust outbreaks which occurred in Sudan in 2003 and continued up to 2005. The main objective is to use GIS and Remote sensing tools to find clear answers for such questions like where and when the initiation of the outbreak started, why and how the outbreak developed, what are the natural and human factors that led to the development and continuation of that outbreak. Meanwhile, answers to these questions will help to propose some lessons to learn for better monitoring and controlling methods of the DL. These objectives would be achieved by analysing historical data of the desert locust during 2003-2005, using ARC GIS system, and the remote sensing images (MODIS EVI and Rainfall estimate).

Chapter Two

Chapter 2

Literature Review

2.1. Introduction

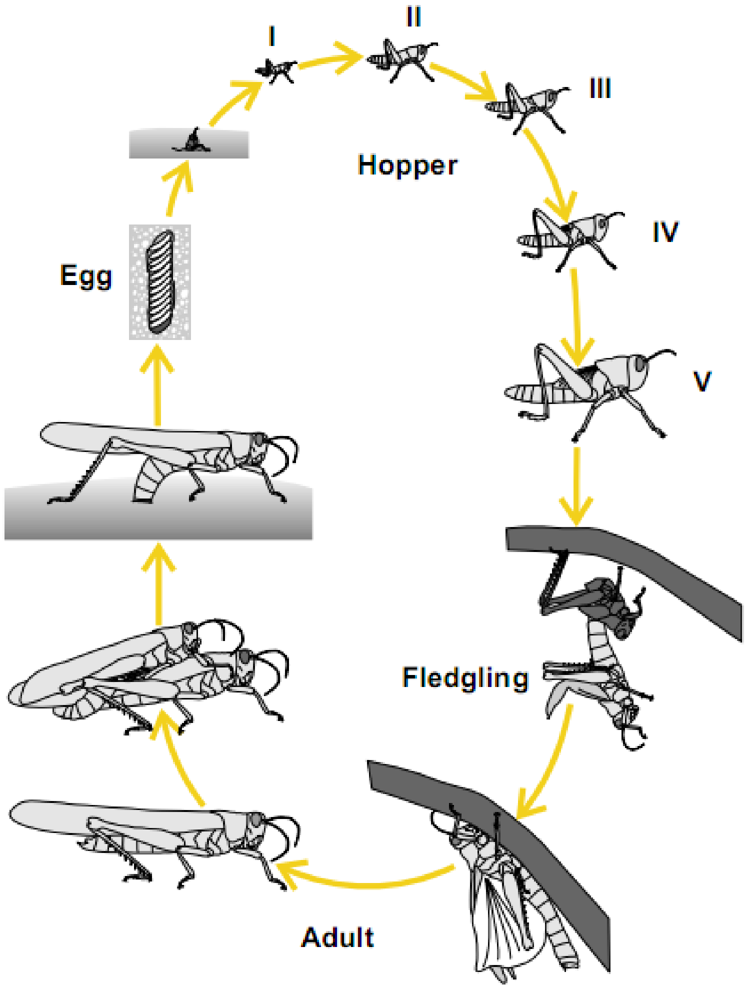
This chapter is an overview of previous studies in the domain of the DL, which includes: the economic importance, life cycle and biology, ecological studies and methods of surveys. Previous studies on the use of the GIS and remote sensing are included in separate sections. In addition to this the last section is an overview of environmental risk models that combine the GIS and remote sensing products for DL monitoring and management.

2.2. The Economic Importance of the Desert Locust

DL invasions normally cause great loss to the crops and pastures in a number of affected countries. They feed on a very wide range of plants, and there are four factors, which mainly contribute to its status as a major pest: the food intake per individual, the range of food plant and parts eaten, the frequency of occurrence of high-density population and the mobility of the population (Suliman 2005). Van Huis (1994) stated that during the last century, DL appeared in the Middle East on different occasions, but the most dramatic invasion in Africa was recorded during 1987 – 1989. A DL upsurge was recorded in 1993 and 1996, which devoured the harvest of Ethiopia, Sudan, Eritrea, Somalia, and Djibouti (Cressman, 1998). The largest invasion during the last 15 years occurred in 2004, in north and West Africa and it affected a number of countries in the fertile regions of the continent. In Sudan, particularly in Kordofan State, around 55% of the food crops were damaged during the 1987-1988 plague (Ibrahim, 2006). The largest crop losses occur when young migrating swarms of immature adults reach cultivated areas. They need to eat at least their own weight (2- 3 g) of fresh vegetation each day and possibly three times as much (Suliman, 2005). As swarms contain 50 million individuals per square kilometre, even a moderate size swarm measuring 10 km^2 could eat some 1000 tonnes of fresh green vegetation daily (Copr, 1982). Desert Locust Control (DLC) costs have been estimated at an appropriate average of $US 38 million per annum, of which almost 40% is financed through international assistance. Over the last decade, there has been questioning as to how justified it is in terms of actual benefit produced, and whether there might be more economically different ways of addressing the threat of the DL. In Eritrea, the study conducted in 1999 which looked at the impact of the1997/1998 DL invasion, found that based on a sample of 401, 20 % of low land farmers lost all their cereal production in 1997/1998. Meanwhile, there was an estimated average value cost of $ US 268 per farmer, 1.5 % of whom were found to have no yield in 1999. All that was attributed to the knock-on effect of the DL (Suliman, 2005). Sudan is considered to be one of the key countries for DL breeding, and its vast winter breeding quarter stretches 147,200 Km^2, and the summer breeding habitat in central Sudan covers an area of 956,360 Km^2 (El-Tom, 1993). For this reason, desert locust surveys and controls are some of the most important services within the national Plant Protection Directorate (PPD) of the Sudan. The Ministry of Agriculture (MOA) allocates 26.39% of the annual budget of the PPD for DL operations and 40% of all are for pesticides that are used in DL Control (Emana, 2002).

2.3. Desert Locust Biology

Desert locust *Schistocerca gregaria* (forskal) consists of two unstable phases, solitary and gregarious. In the solitary phase, the locusts are present as isolated individuals in low numbers, whereas in the gregarious phase they cluster into dense groups forming swarms in a given locality and the transitional phase from solitary to gregarious and vice versa is called the transient (Abdulla, 2004). Its life cycle is like the other grasshoppers and locusts consist of three stages: egg, nymph (hopper) and adult (See figure 1). The estimated time length for the development of desert locust at various stages in its life cycle range between 34 and 90 days, depending on temperature, and the average longevity is 40 to 50 days (Bennett, 1976). Climatic and nutritional factors greatly influence the time required for the adult locust to become sexually mature, and therefore under harsh conditions it can last to more than 40 weeks, but during the suitable conditions 3-8 weeks are long enough periods for the adults to become sexually mature (Pedgley, 1981). Females lay eggs in bare moist soil and 5-10 cm below the surface (Abdalla, 2004). Three egg pods would lie in intervals of one-week, at a minimum of three to fourteen days in the field (Ripper and George, 1965). The incubation period of the DL eggs varied from one breeding area to another, depending on the temperature, in the summer and mason breeding areas 9- 25 days, short and long rain breeding areas of Africa 10-22 days and in the coastal areas around the red sea and the Gulf of Aden 10 – 29 days (Roffey, 1982; Steedman 1990). Solitary hoppers undergo six moults whereas the gregarious moults 5 times. The last moults give rise to immature adults. Depending on temperature the total duration of the hopper development period may vary from 24 -57 days with an average of 36 days (Wardhuagh et al, 1969). Favourable maturation conditions are usually associated with rains. Adults in an area of lush vegetation with maximum temperatures of 35°c or more, and with rain to maintain the vegetation, can probably lay within 3 weeks of fledglings and at the other extreme adults can survive for 6 months or more under dry conditions (Abdalla, 2004).



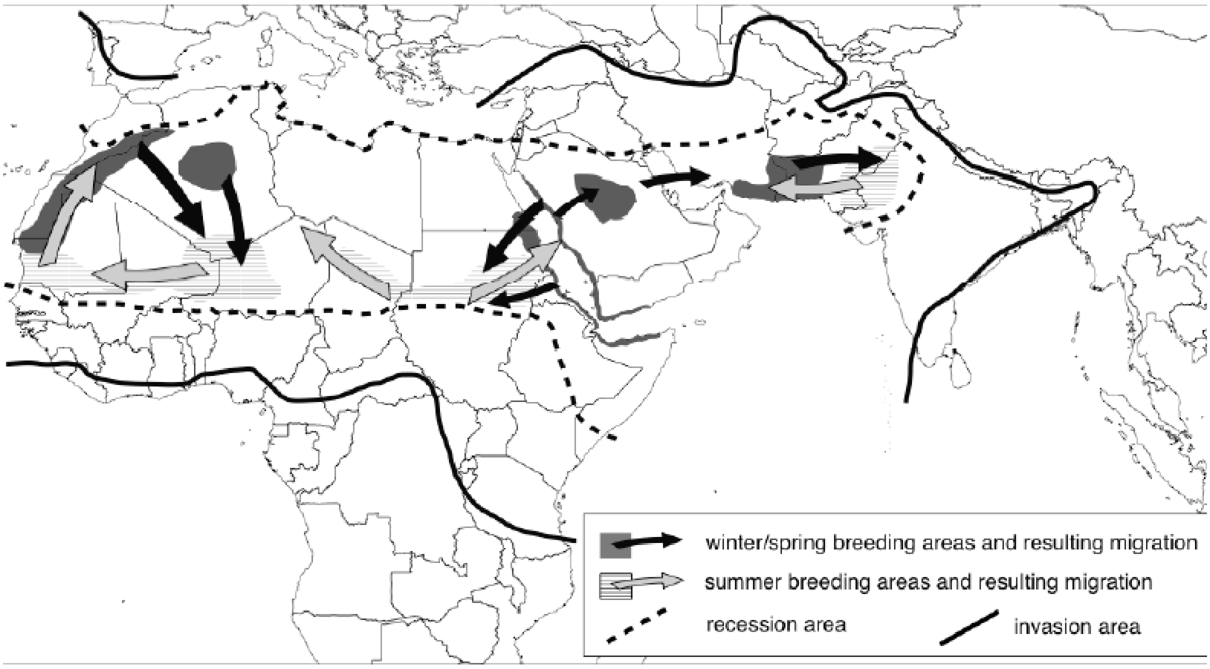
Source: (Symmons and Cressman , 2001)

Figure 2.1: Shows Desert Locust life cycle

2.4. Desert Locust Ecology

The Desert Locust has the widest distribution among all the species and may invade millions of square miles though not all at the same time. The invasion area of the desert locust extends from India and Pakistan to West Africa through the Middle East, and the main factors affecting the desert locust breeding and spreading along these regions includes the rainfall, vegetation cover, soil types, wind, temperature and relative humidity (see figure 2) (Suliman, 2002). Holt and Cheke (1996) state that, there is a positive relationship between locust abundance and rainfall in West Africa and that confirms the importance of the environmental factors, as the variance of locust abundance increases with the increase of the rainfall and weakens with low level rainfall. The invasion area regions are characterised by annual rainfall averaging between 80- 400 mm, and precipitation can be extremely heterogynous in frequency and intensity, as well as differing regionally (See Figure 2). Moreover, rainfall is the most important requirement for the Desert Locust breeding, because it orients the necessary environmental conditions for the breeding, development and multiplication (Suliman, 2005). A minimum of 25 mm rain was required for the ephemeral food and shelter plants of locust to germinate and for successful breeding, successful breeding being defined as an increase in number from mature parents to filial fledglings because the adults frequently emigrate (Bennett, 1976). Rainfall is also found to be influencing the timing of certain developmental milestones in the egg indirectly through soil moisture, the developmental rate of nymphs and sexual maturation of adults through food (DAFF,2011). Frequency of the rain and the duration of the rainy season allow two and a partial third generation of the desert locust to breed, at a higher rate of multiplication than normal, either due to more egg and/or greater survival occurrence, or after one or two high population growths, many approximately synchronous out-breaks appear and an upsurge begins (van Huis, 2006).

Abdalla, (2004) mentioned that Desert Locust are attracted to habitats of high vegetation density and compact structure, because they probably need to protect themselves against unfavourable weather conditions and against the attack of the natural enemies, in addition to their need for food. Locust are able to locate areas of vegetation on which they land, even where these occur only as a few isolated patches, and yet how they do this is still not known. In habitats of evenly distributed vegetation which consist of small, low plants with small areas or bare ground in between, hoppers move over, in and out of the vegetation. Moreover, during the overcast conditions, they spend all day in the vegetation, and it is clear that they spend most of their time in the vegetation in habitats consisting of large, dense low plants (Symmons and Cressman, 2001).



Source: (Rosenberg, 2000)

Figure 2.2: Shows Desert locust areas of invasion and recession; also, it shows the breeding zones and seasonal movement.

2.5. Desert Locust Survey

Desert Locust control strategies have adopted the preventive control measures since early last century, aiming to prevent the development of infestations of large hopper bands or swarms. This requires monitoring of the DL breeding areas on a regular basis and continuing small-scale control operations (Cressman, 1998). Therefore, the affected countries in Asia and Africa maintain regular surveys for monitoring DL habitats and establishing special units responsible for conducting survey and control, which are normally under the supervision of Ministries of Agriculture, Plant Protection Departments. The aim of the survey is timely detection of areas which are potentially suitable for locust development and multiplication (Krall et al., 1997), and this can be achieved by collecting information and assessing locust situations and habitat conditions in the field (Cressman, 2002).

There are two types of surveys included in the assessment survey which are normally undertaken to determine the locust presence in an area or to identify areas of green vegetation where locust are likely to gather, and the search survey in the identified area normally determines the size of the infestation (Cressman, 1998). Moreover, survey itineraries are conducted in the beginning, mid or the end of the rainy season and the collected data normally include information about locust infestation, vegetation status, rain amount and estimates location and date of the survey. Meanwhile, two survey methods which are largely used in the DL domain include the ground and aerial survey; in the first one, food or vehicle transects are used from which the surveyors collect information at each stop point and fill standardized reporting forms and normally Global Positioning System (GPS) is used for referencing the locations. The aerial survey can be conducted in the beginning of the rainy seasons to detect the potential green vegetation and rainfall areas, and in the mid and the end of the season to update the habitat situation.

2.6 .The use of the Remote Sensing DL Monitoring

Remote sensing is defined as the science and art of making observations and measurements about objects without coming into physical contact (Campbell, 2006). It can greatly facilitate monitoring locust population dynamics over large geographical areas. The use of this technique mainly aims in establishing early warning systems that could allow forecasting for regions where locust are detected or likely to be infested. Furthermore, remote sensing products can be used for damage assessment of the desert locust including identification of the extended severity of damage (Ji, et al, 2004). It is also used to detect the potential out-break areas of the Desert Locust (*S. gregaria*) in southeast Asia and northwest Africa (Pedgley, 1973; Heilkema 1977, 1980; Heilkima, et al., 1986; Tucker et al., 1985). Satellites cannot detect desert locust population, (Cressman, 2008), but they can provide continuous overview of ecological conditions favourable for the Desert Locust, at the scale of the affected countries and in near real time. However, the two main environmental factors that strongly influence the population dynamic of the locust can be monitored by the remote sensed imageries, and they include vegetation conditions through direct monitoring of reflectance characteristics and soil moisture conditions driven from satellite rainfall estimation (Pekel, 2010).

FAO started to use 7 km resolution NOAA- AVHRR NDVI and then in 1990 1 km NOAA became available, until it was replaced with SPOT 1 km which is specially designed for vegetation monitoring but which was also superseded by MODIS 250 m resolution (Cressman, 2008). Remote sensing vegetation imagery continued to suffer from two limitations, the accuracy, and the dissemination. The resolution increased southlands of folds but still was not sufficient to detect the thin green vegetation that hosts Desert Locust. So far, with an increase of the resolution, the file size also increased for each image, so this makes it difficult to distribute the high resolution image to the affected countries by internet or FTP because most of the countries have low and erratic connections (Ceccato et al., 2004). FAO and the affected countries used the remote sensing products on a regular basis to identify areas of the highest probability for detecting green vegetation where locust populations are likely to be found, so as to reduce survey areas and prioritize the ground survey checking (Cressman and Hodson, 2009). The NDVI function of red and near inferred spectral bands was quite suitable for detecting vegetation changes by applying the following formula: *NDVI= (R-NIR) / (R+NIR),* Where R is the red portion of the spectrum (0.58 – 0.68) and NIR is the near inferred portion of the spectrum (0.75- 1.4 um). Due to absorbance quantities of chlorophyll, the value tends to be high where there is a large amount of vegetation and low where vegetation is sparse or dry (Tucker, 1979; Tratolos and Cheke, 2006). NDVI may be influenced by factors such as vegetation canopy structure, soil types and atmospheric conditions, so it is substituted with the MODIS image, which has low spatial resolution (250,500, 1000 metres) and high temporal resolution (1-2 days - global coverage) and that allows near real time monitoring of the Desert Locust (Ji, et al., 2004). MODIS also consists of some limitations such as where vegetation was present but not indicated on the corresponding acquired images, and this occurs in parts of Desert Locust recession areas (Cressman and Hodson, 2009). Most recently, innovated multi-temporal and multispectral image analysis methods were found for detecting vegetation cover, in arid and semi- arid areas. Vegetation dynamic maps were updated every 10 days over the whole DL area, at 250 m resolution produced by adopting a complete automatic processing chain designed by combining the daily observation from MODIS (Aqua & Terra) and spot vegetation (Pekel et al., 2010).

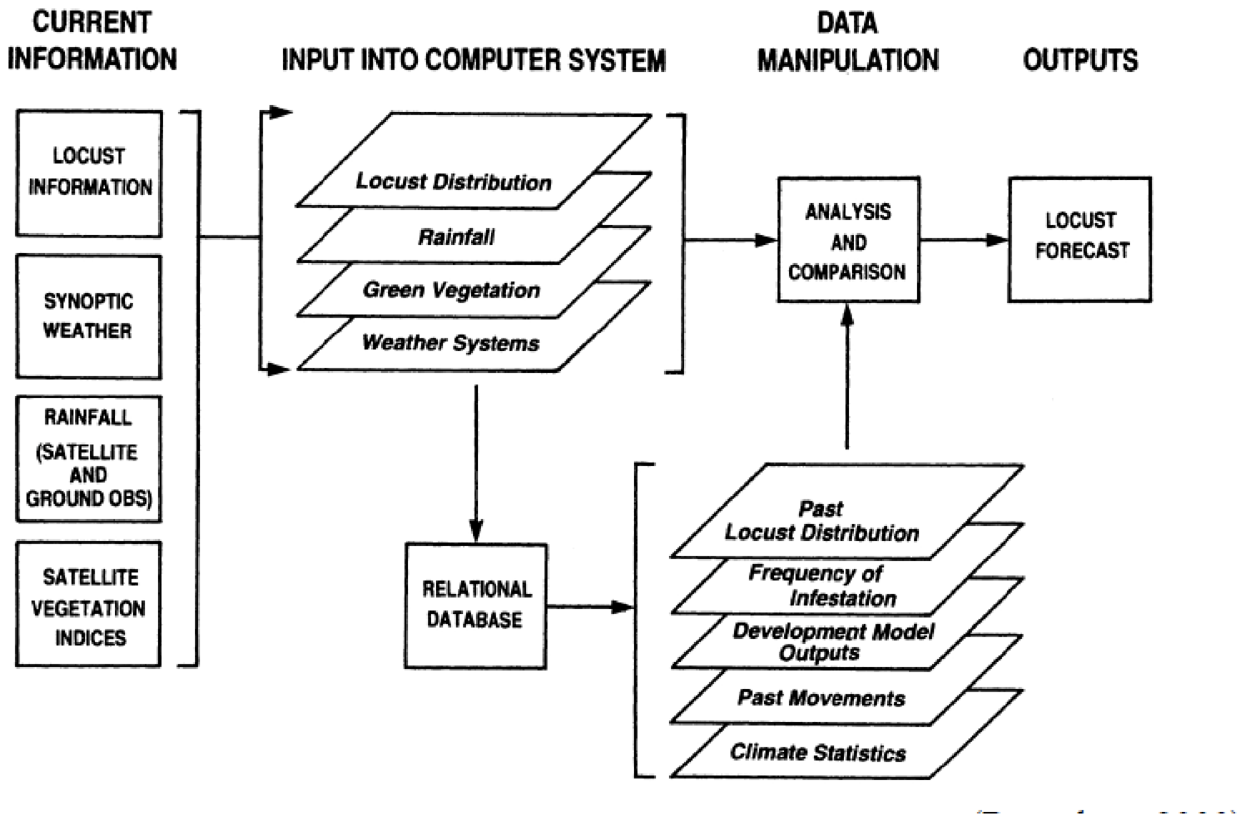
In collaborative work, Columbia University, International Research Institute for climate and society (IRI) with FAO produced daily and decadal remote sensing images, which were used for estimating rainfalls in Desert locust monitoring operations. The images were displayed and downloaded freely from the internet. Moreover, they were considered better estimates to rainfall than some national meteorological stations in DL breeding areas. It is worth mentioning that these images were driven from some sophisticated algorithms available and, had been turned for use in arid areas. In the desert locust early warning system it is important to know where the rain is rather than knowing exact numbers of millimetres (Cressman, 2008).

2.7. The use of Geographical Information System in Desert Locust Management

There have been many attempts to define GIS, but from the viewpoint of the department of environment it is defined as “a system for capturing, storing, checking, integrating, manipulating, analysing, and displaying data which are spatially referenced to the earth.” It can be used to add value to spatial data, by allowing data to be organized and viewed efficiently, by integrating them with other data, by analysis and by the creation of new data that can be operated on in turn, thus meaning GIS creates useful information to help decision-making (Heywood et al., 2002). Moreover, GIS technology can help establishing cross-sectoral communication not only by providing very powerful tools for the storage and analysis, but also by integrating the data base of different sectors in the same format, structure and map projection, thus allowing layers of thematic information to be integrated to provide new insights into sustainable development problems (Bernardi, 2001). However, spatial patterns in insect population could be analysed in GIS. It is also capable to store, organize and analyse diverse sets of geographical data, such as the number of the egg-pods, hopper bands or swarm density and area, temperature, rainfall received, and/ or vegetation at those sites. Moreover, users can query a GIS in order to combine information from physical and environmental variables for any application, and as the environment conditions change, the stored information can be updated and new results generated in a short time. Furthermore, spatial patterns of insect population can be analysed by incorporating insect data in GIS with crop types, and soil for a location to generate new map layers, and also it serves as a tool for analysing interactions within and between various spatial referenced data themes (Latchininsky & Silvanpllia, 2010).

Custom geographical information systems are used by national designated locust information officers in each frontline Desert locust countries, as well as locust forecasters in Food and Agricultural Organization, Desert Locust Information Service (FOA-DLIS) and, they aim to manage and analyse locust and environmental data. In 1996, SWARMS (Schistocerca

WArning Management System) was introduced and was initially operated on a UNIX workstation using oracle databases and Arc Info software. The system was used for managing and analysing survey and control data received from the locust affected countries that consist of details of locust population, ecological conditions, soil moisture, and rainfall (Cressman and Hodson, 2009). RAMSES (Reconnaissance And Management System for the Environment of Schistocerca) is the system used at the national level and was first introduced in 2000, a PC-based system designed to assist national locust units in storing, analysing and disseminating Desert Locust and related environmental information derived mainly from their own data capturing network (See figure 3) **(**Rosenberg, 2000). Both of the two systems allow data to be combined with other sources such as rainfall estimates, MODIS imagery, NOAA rainfall station data, seasonal rainfall and temperature predictions and historical data (from 1930 to present) to assess the current situation and forecast the scale, timing and location of the breeding and migration (Cressman and Hodson, 2009).



Source: (Rosenberg, 2000)

Figure 2.3: Shows GIS, remote sensing and related data processes in the Desert Locust management system.

The Republic of Kazakhstan developed the Decision Support System (DSS) to meet the operational use and forecasting requirements in the locust season. It can handle complex spatio-temporal configuration of locust events, generation of locust sighting as spatial database, cohort distribution based upon known sampling areas and utilization of internet downloaded daily weather data for life stages development (Dutta, et al., 2011). The system used a variety of cartographic and remote sensing sources, so provision was kept for handling of raster, vector, and descriptive data as well as comparison of multiple raster and vector maps analysis of relationships between locust event and bio-climate. It is worth mentioning that, the system was developed on ARC INFO 8.1 NT platforms, and comprises of six modules. Moreover, Australian Plague Locust habitats have been being monitored by using GIS and remote sensing technologies (Latchininsky & Silvanpllia, 2010), and it is well known that the country is one of the pioneers in the practical introduction of remote sensing as well as other technologies such as RADAR and aerial photography (active remote sensing) in locust population management.

The Australian Plague Locust Commission (APLC) is responsible for the monitoring and control of locust populations that pose a threat to agriculture; it established a GIS-based decision support system (DSS), which consists of a set of computerized secondary decision tools that have been added or modified as technology, information sources and operational needs change (Deveson, 2001). They provide access to databases, simulation models and spatial analyses and maps to support both forecasting and operations. The system depends on regular internet FTP data feeds of reported and modelled weather data from the Australian Bureau of Meteorology (BoM) and locust distribution data from surveys as input to development and movement models. The operation of the DSS for forecasting involves modelling critical life stage events and likely outcomes for the current and offspring generation for multiple populations from initial distribution estimates based on surveys or reports. On the other hand, for the operations it provides map overviews and detailed regional views of the current locust situation that combined with relevant environmental conditions and infrastructure. Deveson and Hunter (2002) mention that the incremental development of decision tools has taken advantage of advances in weather and environmental information products, primarily from the Bureau of Meteorology. At the same time, the internet has enabled access to the data in ‘real-time’.

2.8. The Environmental Risk Models in Desert Locust Management

Spatial process models have been constructed for a variety of different purposes. They help structure ideas, to improve our understanding of a problem or to communicate our ideas to others (Heywood, et al., 2006). In addition to that, GIS is needed to couple with other modelling applications or may be able to provide input data and output data capabilities to supplement the other modelling software. Deveson (2001) mentions that, GIS enables the integration of those environmental factors, which determine habitat suitability, and those which influence locust distribution and recruitment, with known distributions to model development across the entire monitoring area. In this way prediction of the timing, reproductive success and likely numbers made of potential populations at any location would be identified. Many examples of integrating GIS and environmental models are found and utilized by regional and national bodies of Desert Locust management. Decision Support System (DSS) found by Australian Plague Locust Commission (APLC), consists of a set of computerised secondary decision tools, that provided access to databases, simulation models and spatial analyses and maps to support both forecasting and operations (Deveson and Hunter, 2002). The DSS was designed to bring together information sources used by forecasting and operations staff, to aid decision-making and to allow modelling of likely outcomes for the current locust generation. It allows GIS to incorporate and display a range of contextual spatial datasets including topographic map data, and at the same time it operates through a range of scales, from a continental synoptic view of major locust species distributions, to regional views of pastoral individual holdings. It uses two models for operation and forecasting: the wind trajectory model, which is a simulation program with an interface to the ArcInfo GIS and uses the collected outputs of the BoM LAPS model (Rochester et al., 1996). It had a trajectory generation module which traces wind vectors at given altitudes from a given set of points and a redistribution module, which uses a specified starting distribution. The model runs a simulated locust flight defined by a set of parameters including take-off time, flight height, altitude, and duration. It also runs backwards so that movements would be analysed from source or destination, and the outputs from modelled flights used as inputs to the redistribution model for subsequent flights to analyse complex migration events. Locust Development Model uses Dymex population modelling software incorporated into the DSS. Dymex (CSIRO) consists of a model Builder program and a

Simulator, which runs specific models with selected weather files (Maywald, et al., 1999). The models incorporate current biological knowledge of each species and are easily modified within the Builder program. Locust development rates are a function of body temperature while recruitment and mortality are linked to rainfall and vegetation state. Dymex run interactively by selecting a weather file for a reporting station, initializing cohort numbers, and specifying the duration of the model run. ArcInfo is used to initiate automatic runs for multiple locations and display the predicted outputs for any date. These started with population profiles from survey data and use weather files calculated from BoM daily rainfall and temperature surfaces. Dymex produced outputs as a table or file with cohort numbers in each defined life stage for each time-step. For the modelled runs, outputs are entered into attribute tables for each habitat unit.

In the Republic of Kazakhstan a Decision Support System (DSS) was developed on ARC/INFO GIS called Geo-LIMIT (Geographically Encoded Locust Impact Minimization Information System). It provides operational decision support for locust habitat suitability, surveillance, prioritization of critical areas and weather conditions on spatial context to enable timely control measures at the field level over the target areas (Dutta,et al.2011). The system function compromises of six modules, among which is the Life cycle builder which uses the daily weather data and analyses the locust breeding suitability under prevailing weather conditions, egg and hopper development and flight suitability. This module works independently and analyses daily weather data downloaded from internet. It uses the data for forecasting climate suitability for breeding of locusts and suitability for flight.

Two different models are used by FAO, DLIS with SWARM GIS when analysing data and forecasting locust development. Desert Locust Egg and Hopper Development Models are mainly used for estimating the rate of egg and hopper development. It helps to understand better any given situation, to estimate when undetected lying or hatching may have occurred, and to predict when hatching and fledging might take place. The model relies on a well-documented relationship between temperature and locust development (Pedgley 1981; Reus, Symmons 1992 and Cressman, 2008). Desert Locust Trajectory Model is used for estimating displacement of adult locust forward or backward in time from any given point (Meteo Consult 1995). It uses six hours meteorological and forecast data for up to ten days, acquired from the European Centre for Medium-range Weather Forecasts (ECMWF), consisting of temperature, pressure, wind direction and speed at several atmospheric levels between the surface and 500 hPa with a resolution of 0.25 - 1.0 degree square. It is worth noting that the models were useful in examining different scenarios and providing early warning of potential invasions to countries at risk (Cressman, 2008).

2.9. Research Hypothesis

In spite of the effort of the national and the international body, Desert Locust outbreaks, upsurge and plagues are still prevalent. Regular surveys and monitoring operations might not be able to detect all breeding sites; this gap could be narrowed by additional research and introduction of efficient systems for monitoring. This study intends to investigate the hypothesis and answer the following questions:

- Vegetation status and rainfall, are they the potential factors that initiate the Desert Locust outbreaks, upsurge and plagues and how?
- How can GIS and remote sensing tools contribute to the minimization of Desert Locust risks?
- How can efficient forecasting for early locusts detection and prevention of Desert locust development be built?

2.10. Expected Outcome

- Identification of the potential factors that led to development of outbreaks to plagues during the study periods.
- Achieving results that would contribute to establishing a better and efficient system of desert locust monitoring and controlling in Sudan.
- Find out key factors for further studies to investigate the issue of the development of the desert locust.

Chapter Three

Chapter 3

Methodology

3.1. Introduction

This chapter defines the study area which is mainly based in the north of Sudan above latitude 12 ˚ N. The study area includes both the winter and the summer breeding zones of the Desert Locust in the arid and semi-arid areas. Data sets are also described and defined in this chapter, which include the historical Desert Locust data received form Plant Protection Directorate, Locust control Centre in Sudan and the remotely sensed data of MODIS EVI and rainfall estimate (RFE) downloaded from Columbia University's International Research Institute for Climate and Society (USA) website. GIS 9.31 and ERDAS Imagine 9.3 were used for data analysis. In addition, Minitab software was used for statistical analysis, mainly binary regression model and t-test.

3.2. Study Area

The study area is located in both winter and summer breeding zones of the Desert Locust in Sudan (See Figur.3). Winter breeding zones cover the areas in the eastern site of the Red sea hills, which extended from the southern borders of Sudan and Eritrea and north up to Sudan and Egypt's borders. It includes mountainous uplands where plant growth is concentrated in channels and river- beds, and coastal plains where vegetation develops in Wadis and alluvial plains irrigated by drainage from the hills (Despland, 2004); it also offers preferable conditions for the desert locusts such as irregular rainfall, high temperatures, and bare soil with habitats of mosaic vegetation (Uvarov, 1957; Eriksson, 2008). The southern coastal plains extend for 190 km to the south of Suwakin town, which is situated on the shore of the Red Sea coast up to the Eritrean borders. It consists of flat sandy coastal plain and Toker delta. The width of the sandy plains is about 10 – 20 km, and behind them are the Red Sea hills, which are rocky, and burn, reaching a maximum altitude of 1740 and 2440 south of Toker.

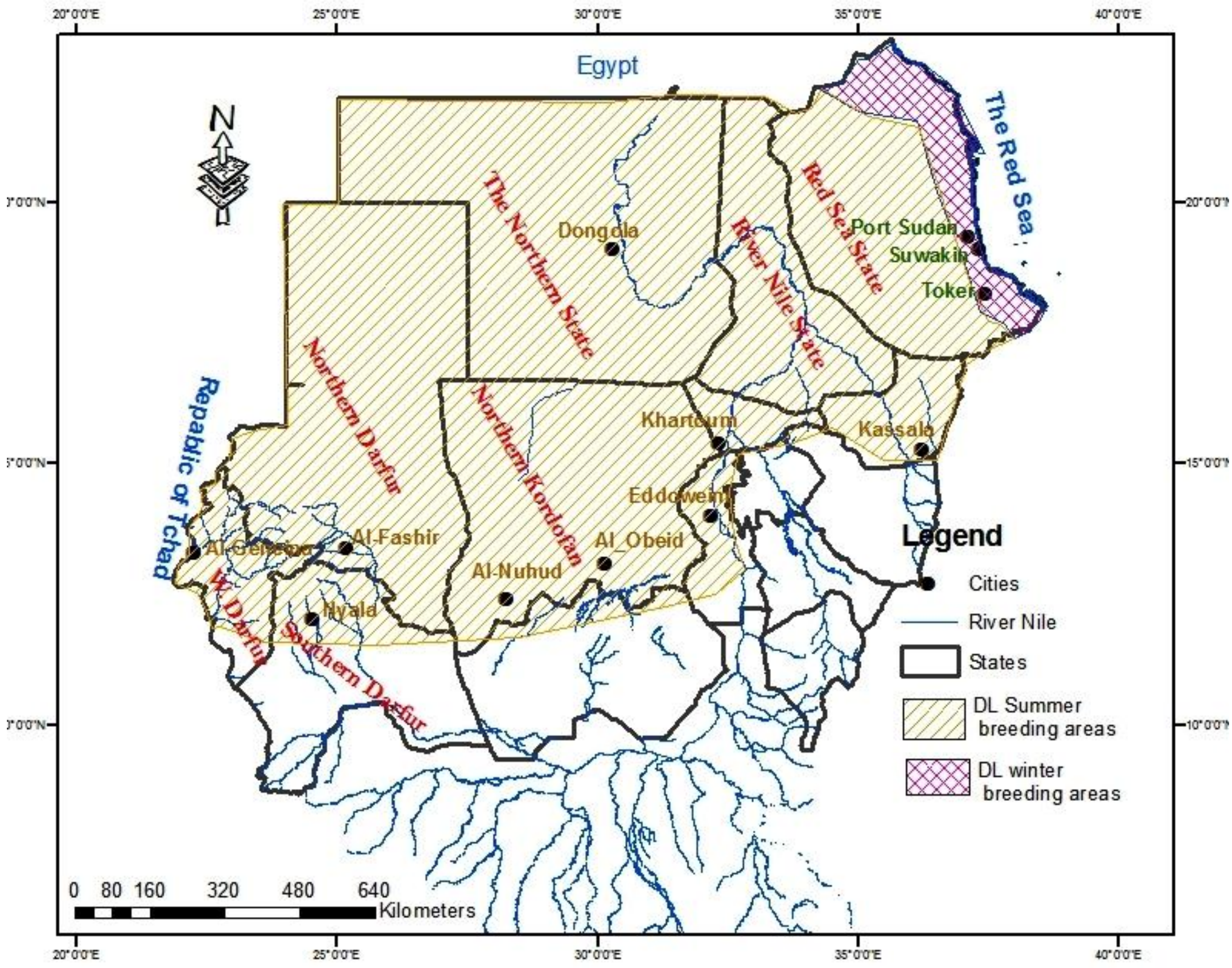


Figure 3.1: Shows a map of Desert Locust summer and winter breeding areas in Sudan

In between the hills are rocky canyons or khors, containing several main plant species preferred by Desert Locust. Toker Delta habitat is quite different from khors or the coastal plains, as it is a cultivated area and consists of fine silt soils that are nurtured by floods arising from rainfall in the Red sea hills and Eritrean highlands that flow down to the Toker delta. The northern coastal plain stretches for about 300 km from Port Sudan city to the Egyptian borders at a width of 10 -30 km, occupied by patches of soft gravel and hard sand, interrupted by several khors, sand dunes and sets of low hills. It also includes the sub-coastal plain habitat which consists of Red Sea hills, small valleys and plains in between the hills that extend for about 85 km in an east –west direction. The Red Sea Hills mark the boundary between the summer and winter breeding areas of the desert locust (Woldewahid, 2003; Eriksson, 2008).

The summer breeding zone covers areas from the borders of western Sudan and Chad to the western sites of the red sea hills and from the latitude 12 00° N and north up to Sudan and

Egypt's borders. The area potential for Desert Locust breeding in Sudan is huge in a total area estimated of 845,000 km2 (CRC-EMPRES, 2011). North of latitude 16 degrees north, the sand sheets of the Libyan and Nubian Deserts extend through to Libya and Egypt; these are bare shifting sands which occasionally support a sparse cover of ephemeral in years of exceptional rainfall. Trees and shrubs occur only in drainage lines, if at all. Low dunes extend southwards to about latitude 13 degrees north, and are mostly stabilized by vegetation; they are long ridges oriented north/south at intervals of 600 -1800 m. In the east and north east, the Atbara River separates the cracking clay Butana plain in the south from the increasingly arid desert of sand, dry Wadis and rock outcrops in the north and east. Jebels become more frequent, especially around Derudeb and east of Kassala along the Ethiopian border. It is worth mentioning that both winter and summer zones have been the origin of several outbreaks within the 20th century, and therefore, the landscape structure during the breeding season must be favorable for desert locust.

3.3. Datasets

There are two types of data collected and utilized in this study: Desert Locust historical data collected in Microsoft excel spreadsheets and considered as primary data; and the other type was the secondary data collected from remote sensing images of MODIS EVI of green vegetation status and rainfall estimates. Both MODIS products and rainfall estimates were already preprocessed and can be incorporated to GIS for display and analysis (Cressman and Hodson, 2009).

3.3.1. Locust Historical Data

The Desert Locust historical data used in the study was collected by survey teams from Plant Protection Directorate of Sudan and they refer back to years 2003, 2004 and 2005. The surveyors collect field observation data on a regular basis in the desert locust habitat, every summer season, which extends from June to October and the winter from November to March. Surveys were created according to information about the current situation of the locust, ecological conditions in the field and the risk that locust population may develop, which required additional monitoring and may be controlled (Cressman, 2002). Normally, surveys were conducted in areas where locusts mostly like to be present, and the collected data includes information about locust situations and habitat conditions in the field. This depends on rainfall distribution, temperature, and presence of the locust in the historical locust habitat (Ghaemian**,** 2003).

There are three types of transect: Foot transect at which the surveyor walks for 100 – 300 meters and counts the flying locust on foot and to the side at a width of 2 meters. Vehicle transects are useful methods of detecting locust in vast sandy plains or areas of large green vegetation, so vehicles are driven at low gears and the flying locust are counted from the front window at 2-4 meter width and a transect length of 1-2 km. It is worth noting that, with both on foot and vehicle methods, transects are conducted either downwind or crosswind to reduce the numbers of counted adults more than one. The third type is an aerial transect which is used to detect areas of green vegetation at the beginning of the rainy season and sometimes big swarms or hopper bands can be detected from the air (Cressman, 2002; Ghaemian, 2003; Mahmoud, 2010).

Both FAO survey and control form (Appendix 1) and Elocust devices are used to record locust information in the field which includes: the name and coordinate of the location, survey date, ecological information such as: habitat types (Wadis, Sand dune, Plain, Crops and Wells), rainfall amount and last rainfall date, soil moisture estimates (Dry, Wet) and also vegetation status (Green, Greening, Dry Drying). Records of locust information were also collected, like the presence or absence of the locust, infestation types (egg fields, hoppers, and adults), phases (Solitary, Gregarious, and Transient) and locust maturity (Mature, Immature). In addition, control information, which consists of control types (Ground, Aerial) and pesticide records (Name, Application rate and type of the pesticide (Cressman, 2001) was also collected. From all the records that are received in the historical data, only the required information was used in the study such as the coordinates of the survey observation point and locust information.

3.3.2. MODIS EVI Satellite Images

The MODIS (Moderate-Resolution Imaging Spectra-radiometer) enhanced vegetation index (EVI) 16-day data with a spatial resolution of 1 km was chosen in this study because of its advantages over other MODIS products. It is claimed by Huete et al., (2002) that EVI was developed to optimize the vegetation signal with improved sensitivity in high biomass regions and improved vegetation monitoring through a de-coupling of the canopy background signal and a reduction in atmosphere influences. In addition, MODIS-EVI is less affected by atmospheric aerosol scattering, and variable soil background reflectance (Huete et al., 1994; Evrendilek and Gulbeyaz, 2008). Moreover, Zhang et al. (2008) mention that the MODIS global phenology product has been produced (MOD12Q2) using 16-day data with a spatial resolution of 1 km, and the product produces key vegetation phenology parameters by fitting piecewise logistic models to time series data from MODIS, and furthermore it detects metrics of the growing season minimum, maximum, and summation of vegetation greenness. The results have been assessed with a limited number of field measurements in North America, indicating that MODIS phenology realistically reflects various phonological dates of ground data. EVI calculated from the following equation:

$$EVI = G\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1\rho_{red} - C_2\rho_{blue} + L}$$

where ρ is atmospherically corrected or partially atmosphere corrected (Rayleigh and ozone absorption) surface reflectance, L is the canopy background adjustment that addresses nonlinear, differential NIR and red radiant transfer through a canopy, and C1, C2 are the coefficients of the aerosol resistance term, which uses the blue band to correct aerosol influences in the red band. The coefficients adopted in the EVI algorithm are, L=1, C1=6, C2 = 7.5, and G (gain factor) = 2.5 (Huete, Justice, & Liu, 1994; Huete et al, 2002).

In this study the spectral profile of MODIS EVI is obtained and used for estimating the biomass of the vegetation cover in the Desert Locust breeding areas in Sudan, for both the winter and summer zones. The spectral profile display is fundamental to the analysis of hyper-spectral data sets. The reflectance (DN) of each band within one (spatial) pixel can be plotted to provide a curve approximating the profile generated by a laboratory scanning spectrometer. This allows estimates of the chemical composition of the material in the pixel (ERDAS, 2009). This is because the spectral profile gives us the reflectance characteristics of earth surface features. It measures the portion of incident energy that reflected. The spectral characteristics vary with wavelength. Different material will gives different effects. For example, chlorophyll in leaves absorbs radiation in red and blue wavelength and reflected green wavelength (ERDAS, 2011).

3.3.3. Rainfall Estimate (FRE)

Rainfall directly or indirectly provides the ecological requirements for breeding and maturation of the desert locust (Rosenberg, 2002), and it mainly determines where there is sufficient growth of vegetation to provide an adequate food supply for Desert Locust (Wilps, 1971). Most of the rain in locust breeding zones of Sudan is associated with the northward advance of the Inter Tropical Convergence Zone (ITCZ), and is of major significance in the timing and phasing of the life cycles of the various species of locust and grasshopper, as well as the location of their feeding and breeding areas (USAID, 1990). Satellite sensors, meteorological numerical models, and rainfall algorithms have improved since the late 1990s, and new products have been developed to estimate rainfall on a local, regional, or global level. Model-based rainfall estimates are relatively accurate in determining rain quantity while satellite-based products are better at estimating the spatial distribution of rainfall (Pinker, Zhao et al. 2006). Pedgley (1981) mentioned that larger rainfall events are of particular interest because they can start or maintain upsurges, and they are often associated with certain synoptic situations and their possible occurrence can be estimated from daily weather maps. FAO DLIS has been using IRI rainfall estimates since 2006 and has found that they are a much better estimate of rainfall than data from the relatively few national meteorological stations in the Desert Locust breeding areas (Cressman, 2008).

Satellite images of rainfall estimates were downloaded from websites that provide product estimates of ecological conditions and rainfall events in the Desert Locust recession area. It is a collaborative work between DLIS and IRI (IRI was established as a cooperative agreement between NOAA's Climate Program Office and Columbia University). 10 days of accumulated rainfall estimates are used in this study. The products are produced on estimates from the Climate Prediction Canter Morphing technique; it produces global precipitation analyses at a very high spatial and temporal resolution. This technique uses precipitation estimates that are derived from low orbital satellite microwave observations exclusively, and whose features are transported via spatial propagation information that is obtained entirely from geostationary satellite IRI data. It is worth mentioning that this technique is not a precipitation estimation algorithm but a means by which estimates from existing microwave rainfall algorithms are combined. Therefore, this method is extremely flexible so that any precipitation estimates from any microwave satellite sources can be incorporated (Joyce et al, 2004).

3.4 . Data processing in ARC GIS 9.3

Desert Locust survey and control historical data for summer and winter seasons of the years 2003, 2004, and 2005 are received from PPD, Sudan in Microsoft excel spreadsheets every month in a separate file. Summer seasons included months from June to October and the winters from November to March. The data was sorted out into seasons and categorized according to locust infestation into two options of locust presence or absence, and then two excel spreadsheets were prepared for each season.

The excel spreadsheets, which contain the locust records were converted into shapefiles by using ARC GIS 9.31 software, then they were projected to Geographic Coordinate System: GCS_WGS_1984, Datum: D_WGS_1984, as had been done for all the MODIS EVI satellite images and the map of Sudan. Each season shapefiles were displayed on the map of Sudan (the new map after separations of the south Sudan), at which each of them represents either the presence of Locust or absence with a given symbol such as orange circles for the Locust Absence and blue triangles to the presence of Locust. Lastly, shapefiles were overlaid as event layers to MODIS EVI images of maximum value to each season for visualization and analysis.

3.5. Data processing in ERDAS Imagines

MODIS EVI 16 day composite and rainfall estimate 10 days composite satellite images for the seasons of summer 2003, summer and winter 2004, and 2005 respectively were collected from IRI web site. The ultimate purpose was to extract spectral profiles form the satellite images to discriminate vegetation cover and estimate the total rainfall amount for each season separately discover their effect on the initiation and distribution of the locust. The extracted spectral profiles were then used to correlate the maximum values of EVI and total rainfall to each of the season. Multilayer or bands are required for extracting the spectral profiles, so that 10 single layers of EVI and rainfall estimate satellite images for summer seasons and 15 others for winters to the year under the study were acquired. Ci et al. (2011) mentioned that the spectral of vegetation was affected not only by soil, the surrounding environment, shadow, soil colour, moisture, and other factors, but also by air space - phase change, so there needs to be a comprehensive multi-parameter analysis. Nevertheless, fortunately, the EVI is MODIS-specific and offers improved sensitivity in high biomass regions while being less sensitive to atmospheric aerosol scattering (especially smoke from burning vegetation). It also minimises the influence of background interference caused by bare soil reflecting off the ground (Huete et al., 1999, Neterler, 2005).

Layers stacking for both EVI and rainfall seasonal single layers are processed in ERDAS Imagines 2010, and then the projection is assigned to Geographic Coordinate System GCS_WGS_1984 with datum D_WGS_1984. When the stack images were ready the historical data shapefile of every season was overlaid to its corresponding season image to display the training sets, which were represented from the ground truth data collected by Desert Locust survey and control team of PPD, Sudan. After that, the training signatures were selected for extracting the spectral profile. Each season profile data were saved as files with default extension ending in (.sif), and the results obtained in these files were transferred to Microsoft excel files, so further preparation such as arrangement of the data in columns and rows were done.

3.6. Statistical Analysis

Binary logistic regression analysis and t-test analysis is performed in this study using Minitab software. In this study the entire purpose of the binary logistic regression analysis was to look for the relationships between the categorical variables, which in our case was the presence and the absence of the desert locust and the predictive variables considered as the maximum, minimum EVI values, total rainfall, vegetation height and the coordinates. The data were prepared separately in list tables every year. The dependent variables were given numbers according to the category such as locust presence (1) and locust absence (0). After preparation of the data, they were copied and pasted to Minitab and binary logistic regression model run. Results were obtained where P- values of significant answers were selected and prepared in tables for interpretation.

Two t-test statistical analyses are applied in this study. T-test is most commonly applied when the test statistic follows a normal distribution if the value of a scaling term in the test statistic is known T_TEST (Bower, 2000). Maximum EVI value and total rainfall were compared by adopting methods of year versus year (2003 versus 2004, 2004 versus 2005 and 2003 versus 2005), and for examining which of the years appeared to accommodate many resources, that might strongly influence the development of Desert Locust. Results from the analysis obtained from t –values and P- values determine the significance of the tested variables (Minitab, 2011).

Chapter Four

Chapter 4

Results and Discussion

4.1. Introduction

This chapter covers the interpretation and analysis of the obtained results, which were an outcome of processing and analysing of the datasets mentioned in the methodology chapter. Desert Locust appearance seasonal maps were generated from overlaying DL historical data shape files, with MODIS EVI of maximum values to each season and the map of Sudan with administrative states borders. The purpose of the maps was to study the seasonal variations along the study period. Bar charts showed maximum EVI values and total rainfall estimates for each separate season and correlation chart created, to find out the relationships between the tested variables. Statistical analysis, binary regression model, and t-test results are shown in tables at the end of the Chapter. Discussions of the obtained results and comparisons with previous studies carried are out to support the fulfilment of the study objectives.

4.2. Seasonal Variations

4.2.1. Summer 2003

Desert locust distribution was extended into eight states along the summer breeding zones of Sudan during 2003, as shown in map figure (4.1), where a survey was conducted on the states of Northern Darfur, Northern Kordofan, White Nile, Khartoum, the Northern, Nile, Kassala and Red sea state. Locusts seen in all surveyed areas accept the Northern state. As stated in the literature review, locust surveys aim to assess the locust populations quantitatively (numbers) and qualitatively (kind) (Popov, 1975) and the quantitative studies depend on the understanding of the environmental influences on the daily behavioural cycle (Ovarov, 1977).

MODIS EVI image showed green vegetative areas in almost all locust detected areas. However, they varied in degree of greenness, form dark green as can be seen in Darfur and Northern Kordofan, green in White Nile state and Kassala to light green in the Red Sea state.

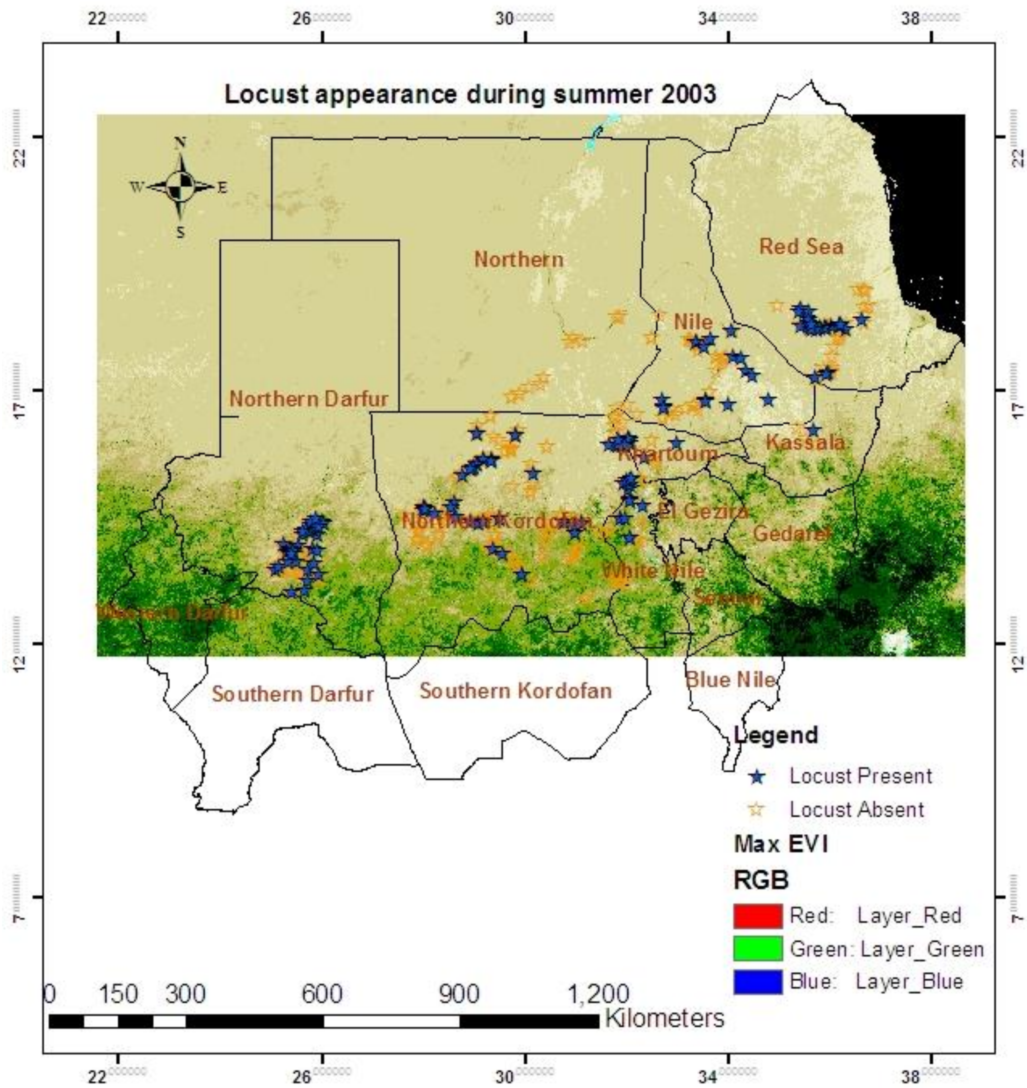


Figure 4.1: Showing vegetation abundance acquired as maximum MODIS EVI satellite image as a composite of the first decade of August and Locust infestation during the summer 2003, the blue stars symbolizing the presence of Desert Locusts and the orange ones their absence.

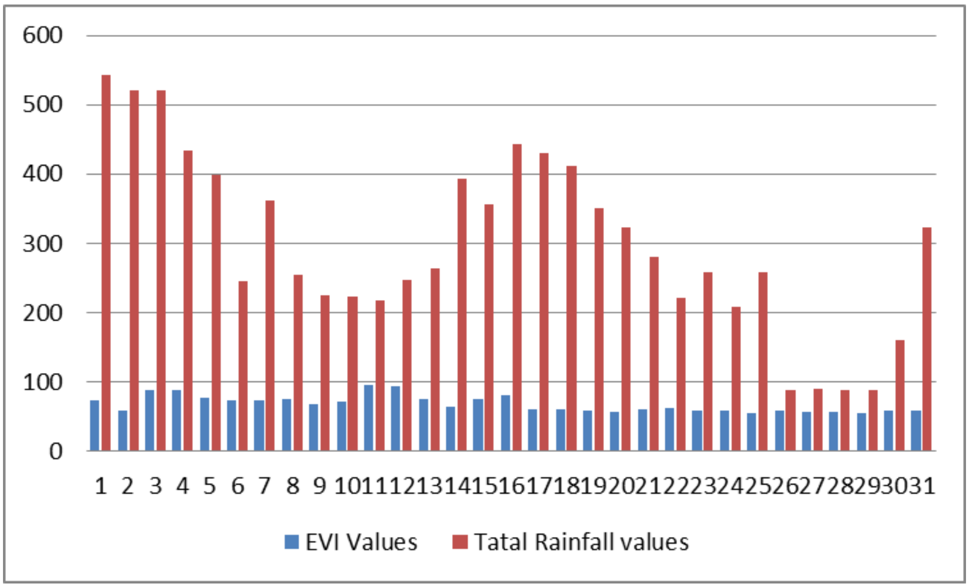


Figure 4.2: Maximum EVI values (blue bars) and Total Rainfall (Pink bars) during the season summer 2003.

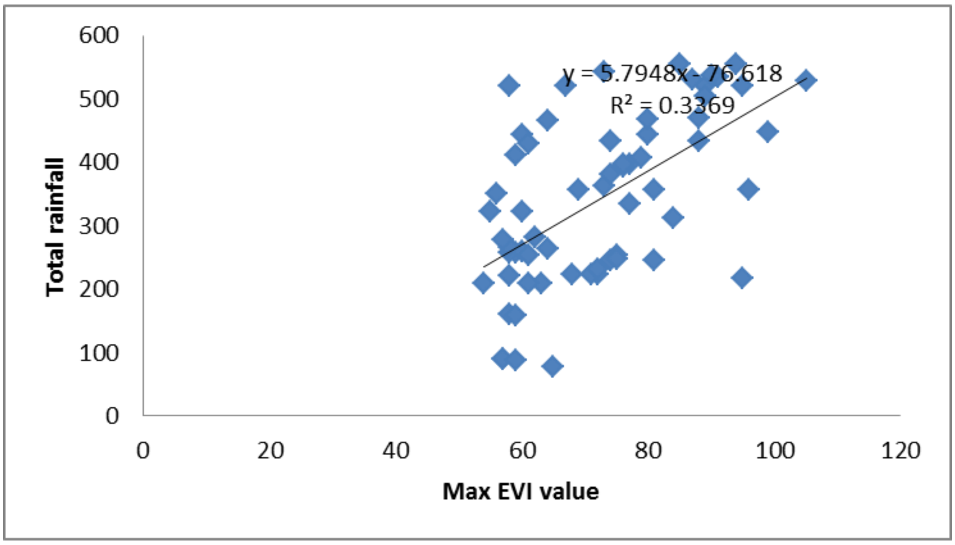


Figure 4.3: Correlation between maximum EVI and Rainfall during summer 2003.

Quantitative amounts of maximum EVI and total rainfall for the season 2003 are extracted from MODIS EVI and Rainfall (RFE) satellite images are represented in figure (4.2). The results showed medium to high vegetation heights, which were sampled from survey training areas. However, total rainfall varied in the same samples. It started from the lowest amount of less than 100 mm, and increased to medium (100- 250 mm) to each the highest (250- 500 mm). As mentioned in the introduction, Desert Locust are characterised by seasonal rainfall averaging between 80 and 400 mm annually, which would vary dramatically from year to year with annual rainfall being up to 70% above or below average (Magor, 1994). From the observation of the above chart, it can be determined that areas where received high levels of precipitation had formed a higher magnitude of vegetation cover. So far, a strong correlation has been found between rainfall amount and maximum EVI values which were indicated by (R^2 = 0.3369) where (R= 0.5804), as shown in figure (4.3). Therefore, if the rainfall increased in the amount, the vegetation magnitudes increase accordingly and that might promote the development of Desert locust. Thus, successful breeding of Desert locust occurred during summer 2003 although there were some areas of green resources such as in the West Darfur state and some parts of Northern Darfur and Northern Kordofan but no Locust were reported there.

The quantitative assessment of the amount of vegetation cover and rainfall estimated during summer 2003, which resulted from the analysis of EVI and rainfall estimate (RFE) satellite images, showed a variation in the quantities in all summer breeding areas of Sudan. While Darfur and part of North Kordofan showed high vegetation growth, the other states appeared to have low volumes of vegetation cover. However, the rainfall estimate had increased more than the normal rate (400 mm), yet the distribution might not be equal in all areas, so that the greenest areas might have received much more precipitation than the others. This might be one of the factors that largely contributed to creating favourable conditions and promoting the appearance of the DL in mentioned states. Moreover, a strong correlation of 58% was found between the two factors. However, rainfall was considered the most important requirement for the Desert Locust breeding, because it orients the necessary environmental conditions for the breeding, development and multiplication (Suliman, 2005). Anyamba et al. (2005) claim that, persistence of rainfall, moist conditions and availability of adequate supplies of food over a large area leads to large-scale breeding and subsequent increase in Desert Locust population and concentration. The FAO Emergency centre for Locust Operations (ECLO) during summer 2003 reported that small-scale breeding was detected in Northern Darfur, Sudan and was likely to be in progress in Northern Kordofan at the beginning of the season, reflecting in the fact that locust numbers slightly increased and the breeding continued in the mentioned stats. Eventually, at the end of the season in the River Nile Locust outbreaks were developed where small swarms were detected (FAO, 2003). High rainfall that received during summer 2003 in River Nile state, led to increase the amount and extent of green vegetation cover. The vegetation cover remained green for long time, due to nature of heavy clay soil along river Atbara and the Nile, which preserve the ground water for long periods. locust breeding was occurred locally and gradually led to increasing of swarms numbers , as well as the situation had attracted many swarms towards green areas of River Nile state arrived from neighbouring border states, where most of the vegetation started to drying in the end of the rainy season.

Some areas were found to have much vegetation cover, but they were free of locust. That might be referred to the unsuitability of the habitat or inaccessibility reasons which hinder the survey team from reaching the areas for checking, such as insecurity reasons. This is one of the reasons that may promote the initiation of DL outbreaks, because the undetectable locust could move freely in those areas, then breeding and multiplying in numbers occurs and eventually form locust plague. So far, this habit has been observed by Cressman (2008) who stated that Locust plagues are initiated by uncontrolled local outbreaks that develop in the frontline countries, which are extended from Mauritania in Africa to India. Although Van Huis, et al. (2006) did not provide clear cut evidence for of the initiation of plagues from the concentration of scattered locust followed by successful breeding and grangerization, or from the carry-over of swarms during recessions, it is clearly known that locust move seasonally between complementary breeding zones during recessions.

4.2.2. Summer 2004

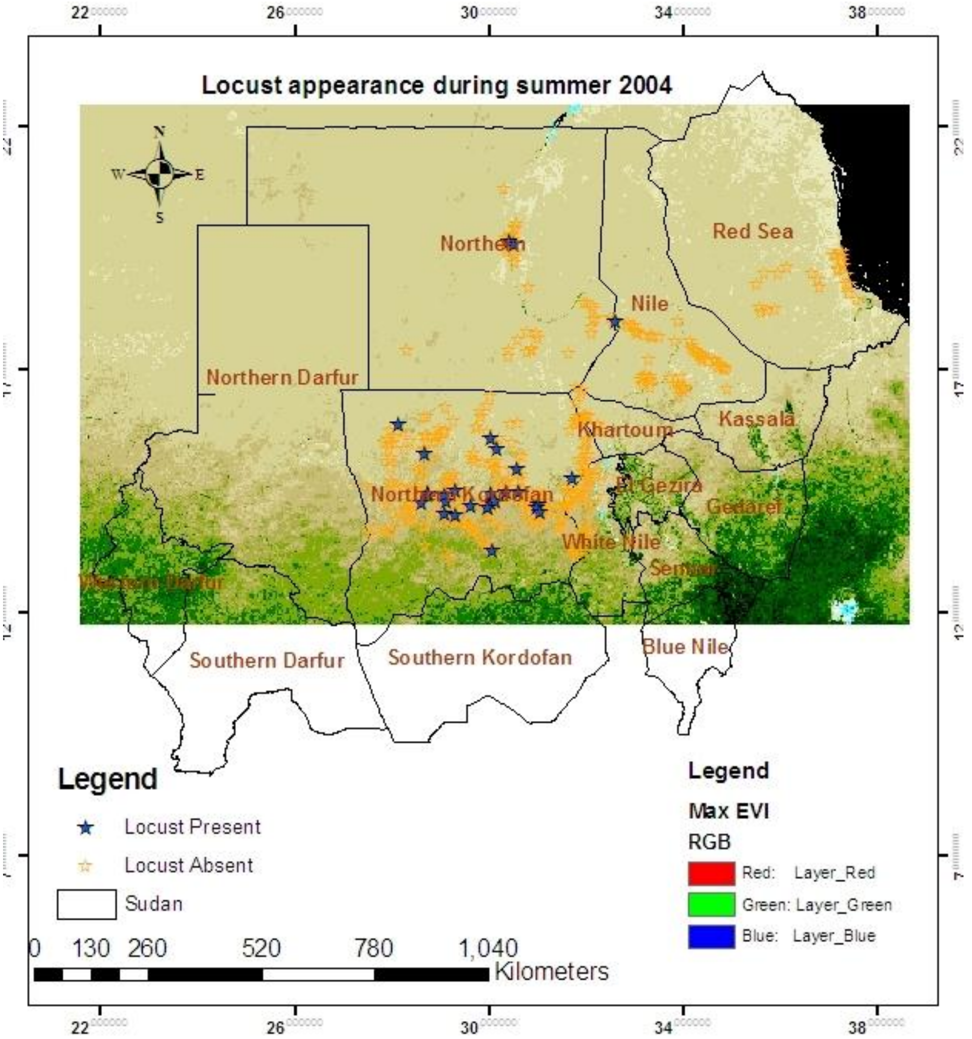


Figure 4.4: Showing vegetation abundance acquired as maximum MODIS EVI satellite image as a composite of the 2nd decade of July and Locust infestation during summer 2004, the blue stars symbolizing the presence of Desert Locusts and the orange ones their absence.

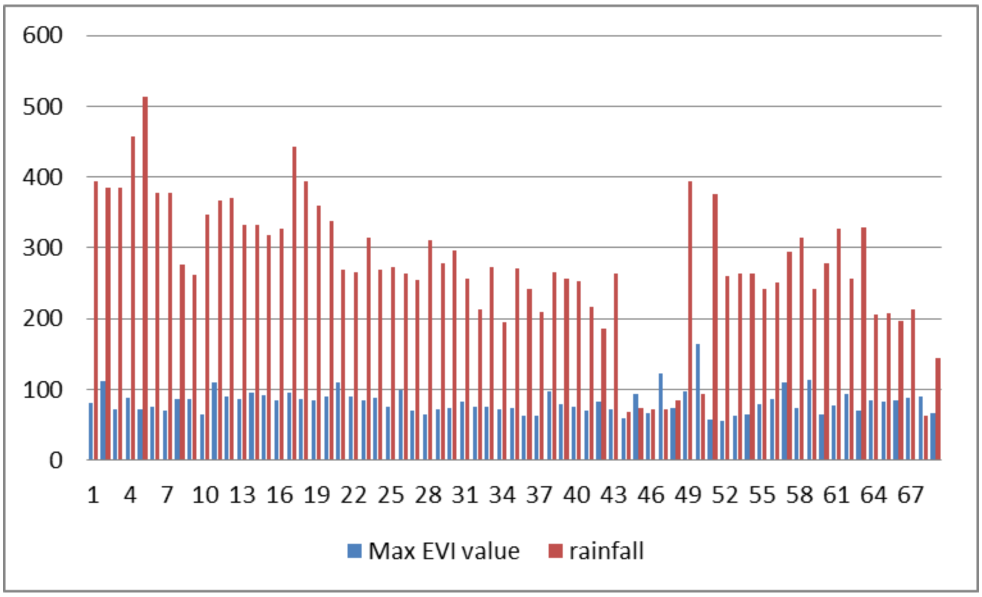


Figure 4.5: Maximum EVI values (blue bars) and Total Rainfall (Pink bars) during summer 2004.

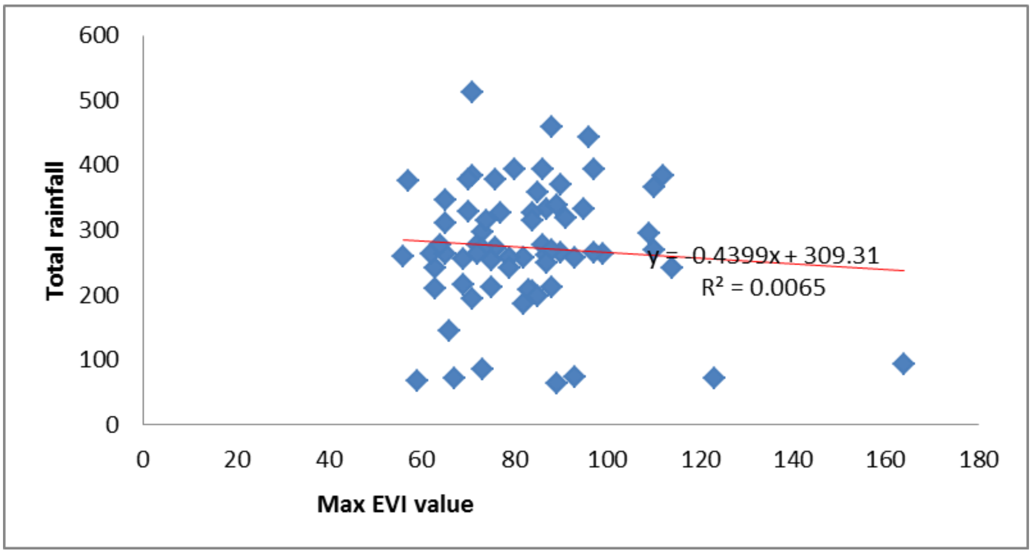


Figure 4.6: Correlation between maximum EVI and Rainfall during summer 2004.

Desert Locust during the summer season 2004 were mainly concentrated in Northern Kordofan, White Nile, Khartoum, River Nile, and Northern parts of the Red Sea States, as can be seen Map in figure (4.4). Most of the detected locusts can be seen in Northern Kordofan and a few of them in the River Nile and the Northern states. The EVI image reflected a very low amount of vegetation cover, which was shown on the map as light green or lighter colours, which indicates the absence of vegetative cover. Figure (4.5) shows most of the training samples have maximum EVI values less than 100 with variations from one sample to another. At the same time, rainfall in most of the training points were less than 400 at the higher amount and within the range of 250 to 300 at the medium level, whereas the low level of rainfall shows an amount less than 100 mm. No positive correlation was found between the maximum EVI value and total rainfall which is indicated by R^2= 0.0065 where R = 0.0803, as shown in figure (4.6). The results indicated that the summer 2004 was a calm season for Desert Locust development and that might be due to scarcity of the rains and consequential poor vegetation volume. Although there were some green areas in Northern Darfur and Western Darfur states, no surveys had been conducted there. Intensive surveys conducted during summer 2004 resulted in detecting few locusts in Northern Kordofan, along the river Nile and the North (FAO, 2004 a). The season had seen low rates of precipitation less than the normal average (400 mm) in most areas and even the EVI satellite image showed a very low volume of greenness. Furthermore, no correlation was found between the rainfall estimate and EVI. Although there was a scarcity of rain and food, still locust had appeared in some areas of Northern Kordofan, which might be due to the ability of the solitary locust to survive with minimum quantities of food plants. Kennedy (1939), Ellis and Ashall (1957), (Roffey and Popov 1968) and (Maeno and Tanaka 2011) mentioned that patchy distributions and low quantities of food plants might cause temporary local grangerization in both migratory Locust *(Locusta migratoria*) and Desert Locust because locusts gather and interact locally with one another. Meanwhile, gregarious hatchlings express better developmental performance and survivorship under low quality food conditions than solitary ones (Maeno and Tanaka, 2011). So far, (Abdalla, 2004) has stated that adults in an area of lush vegetation with maximum temperature of 35°c or more, and with rain to maintain the vegetation, can probably lay fledglings within 3 weeks and at the other extreme adults can survive for 6 months or more under dry conditions.

4.2.3. Winter 2004

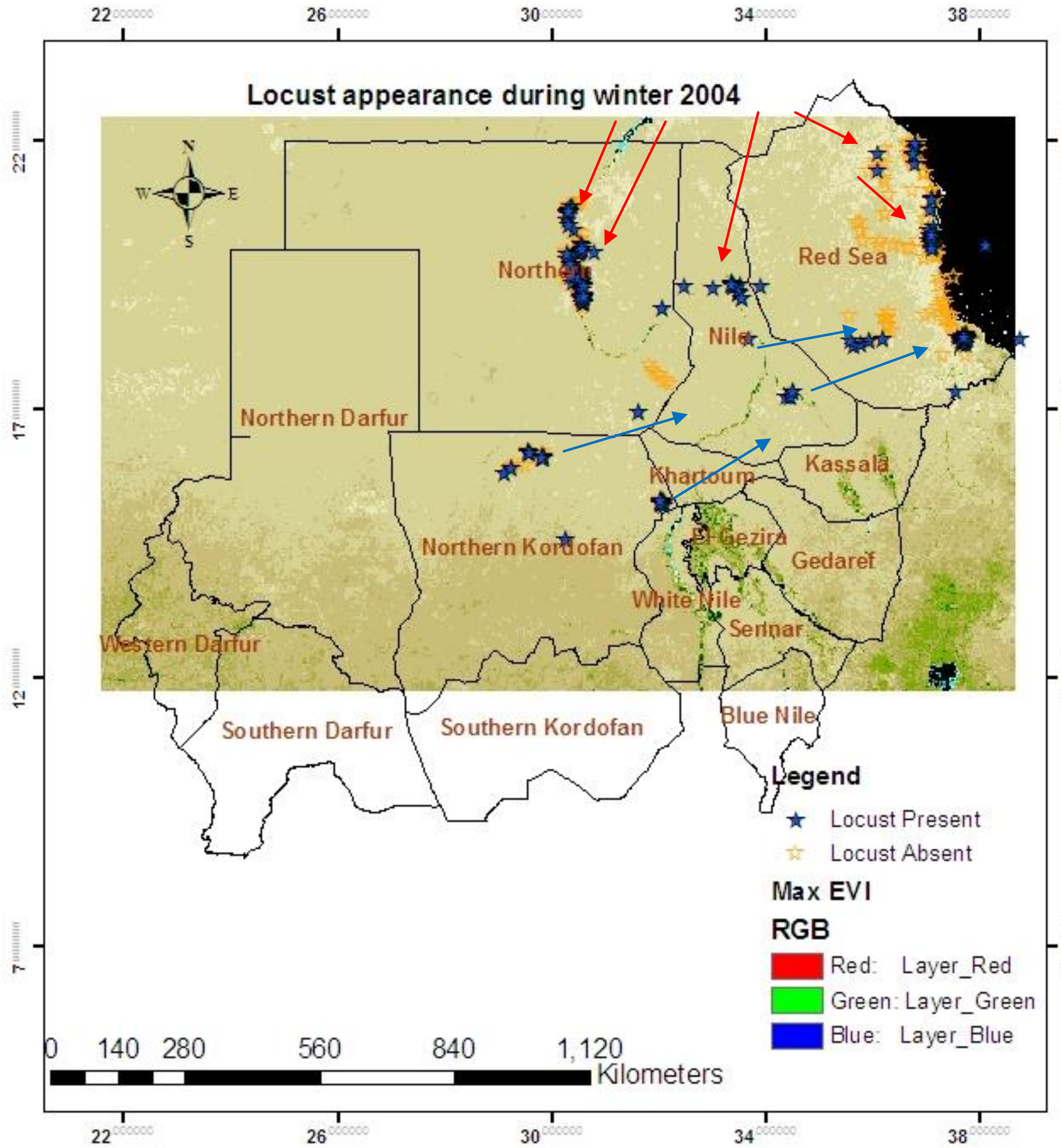


Figure 4.7: Showing vegetation abundance acquired as maximum MODIS EVI satellite image as a composite of the 2nd decade of December and Locust infestation during the Winter 2004, the blue stars symbolizing the presence of Desert Locusts and the orange ones their absence.

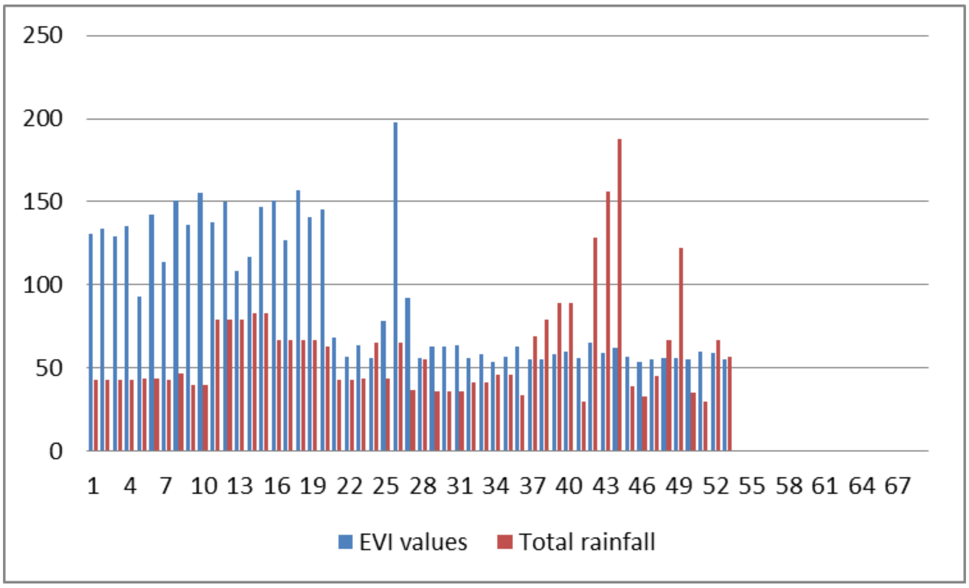


Figure 4.8: Maximum EVI values (blue bars) and Total Rainfall (Pink bars) during winter 2004.

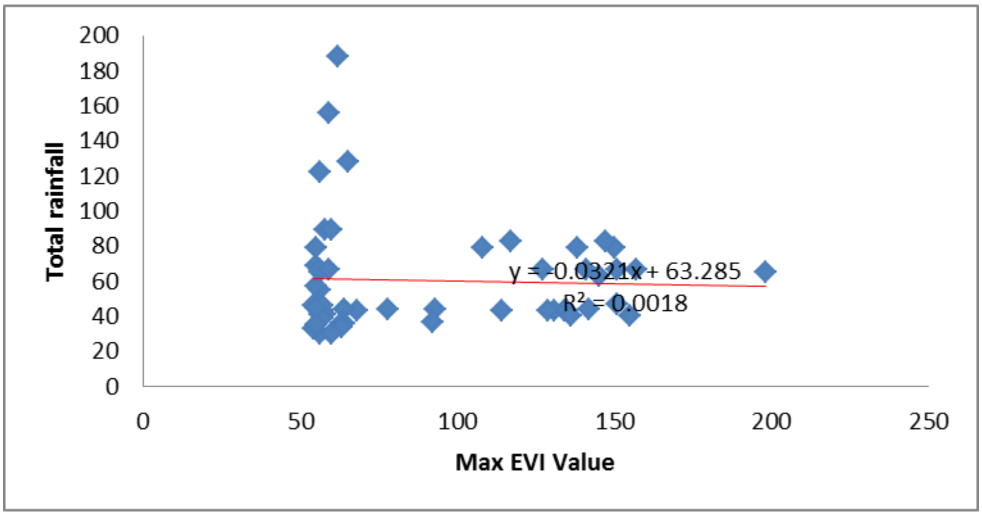


Figure 4.9: Correlation between maximum EVI and rainfall during the winter 2004.

Normally, locust breeding in winter zones is restricted to the coastal plains, which extend 20 – 30 km, in between the seashore and the red hills, along the coast from Eritrea and Sudanese borders and back to Sudan and Egypt once more, as stated in the methodology (Despland, 2004). Yet, as shown in map figure (4.7) during winter 2004, the locusts appeared in summer breeding areas in Red sea summer breeding zones along the Nile and its tributaries in Northern and the River Nile states, as well as entire summer breeding areas of the Northern Kordofan state. Along the coast, Locusts were concentrated in Toker Delta from the southern parts and in the middle part of the Red Sea coast (FAO, 2004 b). The EVI satellite image showed all the areas were dry, except some patchy green areas along the river Nile and the tributaries banks as well as some light green areas in the southern boarders of Sudan and Eritrea. Maximum EVI on Figure (4.8) shows very high values in some observation points to more than 150 and more than 500 in others. On the other hand, the total rainfall shows a very low amount at maximum 195 mm and less than 50 mm during the whole winter season of 2004. Non-positive correlation was found between maximum EVI and total rainfall at which R^2= 0.0018 where r = 0.0424 in figure (4.9). This indicated that there was no influence between the tested variance on each other. Therefore, the rainfall had no effect on vegetation status during winter 2004. Results showed that during winter 2004 DL distribution had different spatial patterns and even extended to the summer zone. Most of the local breeding locust showed migration movements towards Toker Delta, which might be due to prevailing favourable conditions there, because it is a cultivated area and consists of fine silt soils which have been nurtured by floods arising from the rainfall in the Red sea hills and Eritrean highlands which flowed down to the Toker Delta (USAIAD, 1997). Desert Locust normally look for green vegetative areas and migrate to distances estimated at 3000 – 4000 km (Rainey, 1963; Pedgley, 1981; Suliman, 2005). In addition, the local climatic conditions determine the occurrence of locust populations in and near cultivations. This is probably because the food plants and other vegetation in these areas remain green for a longer period of time (Maxwell -Darling, 1936; Suliman, 2005). At the beginning of the winter season, all migrated locust form summer breeding zones moved to the south part of Red Sea. There Toker Delta was the only green area, as shown in figure (4.8) with blue arrows. Meanwhile, locust that can be seen in the northern part of the Red Sea coast and part of River Nile, as well as the Northern State, invaded the green areas of the early hatchlings and swarms that migrated from Egypt downwards to Sudan (FAO, 2005 b), as illustrated by red arrows on the map. Although the green areas attracted the locust into the Toker Delta from the summer breeding zone, Egypt borders to the River Nile and the Northern States and part of the North Red Sea coast still used remote sensing MODIS EVI images and considered them to have fewer abilities to discriminate vegetation areas from bare soil. Nevertheless, it allowed identification of potential habitats of the Desert Locust and that was an achievement of remote sensing data in the domain of the Desert Locust (Tappan, Moore, & Knausenberger, 1991; Cherlet & Di Gregorio, 1993; Latchininsky and Sivanpillai, 2010). The absence of the correlation between the rainfall and EVI values had not affected the locust activity during this season, which was because locust migration targeted the green areas along the River Nile and the Toker Delta. Both of the cultivated areas depend on a mechanized irrigation system, and flood inundation respectively. Therefore, the rain did not have a role during this season in establishing complementary breeding areas for the Desert Locust.

4.2.4. Summer 2005

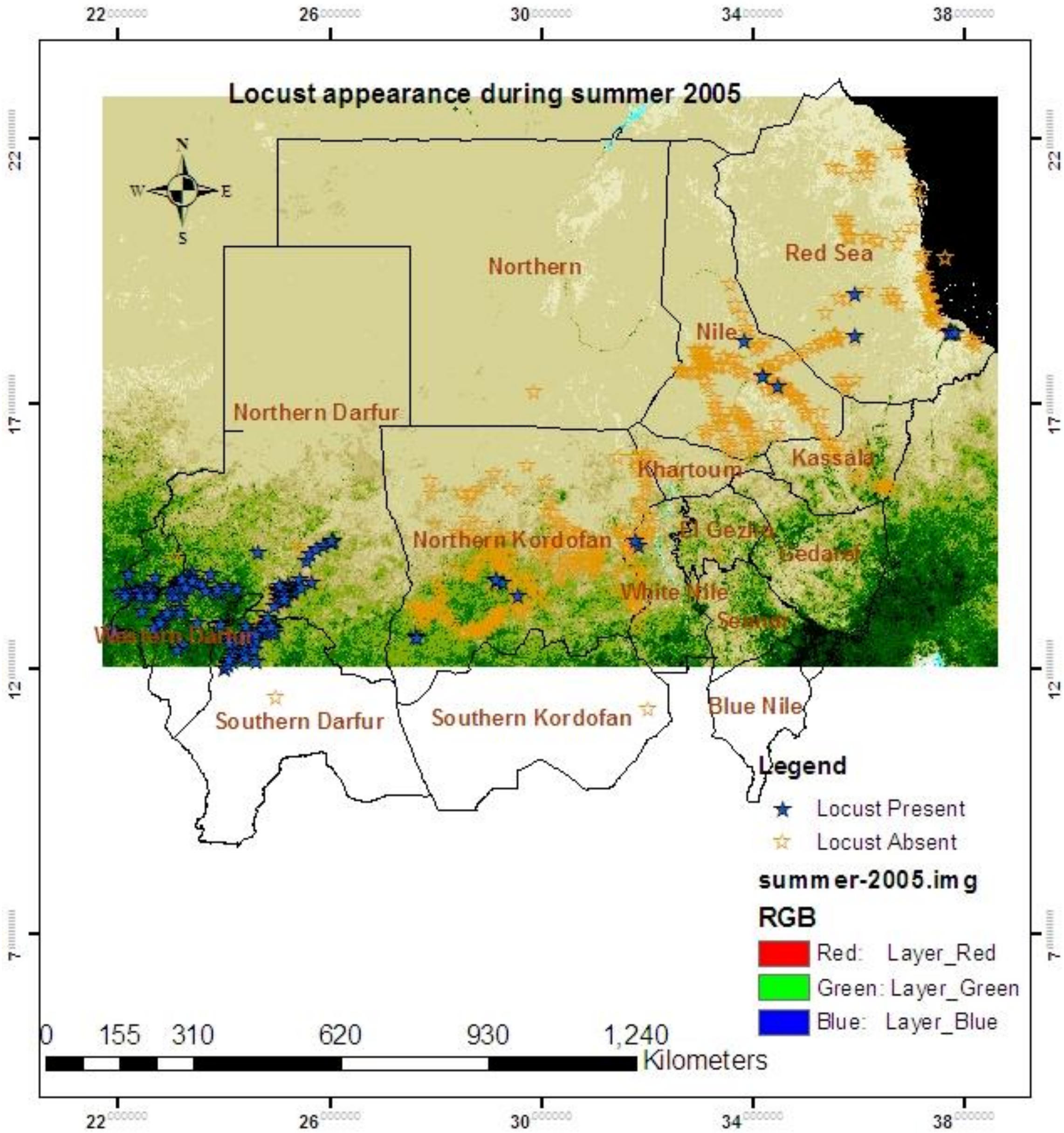


Figure 4.10: Showing vegetation abundance acquired as maximum MODIS EVI satellite image as a composite of the 1st decade of December and Locust infestation during summer 2005, the blue stars symbolizing the presence of Desert Locusts and the orange ones their absence.

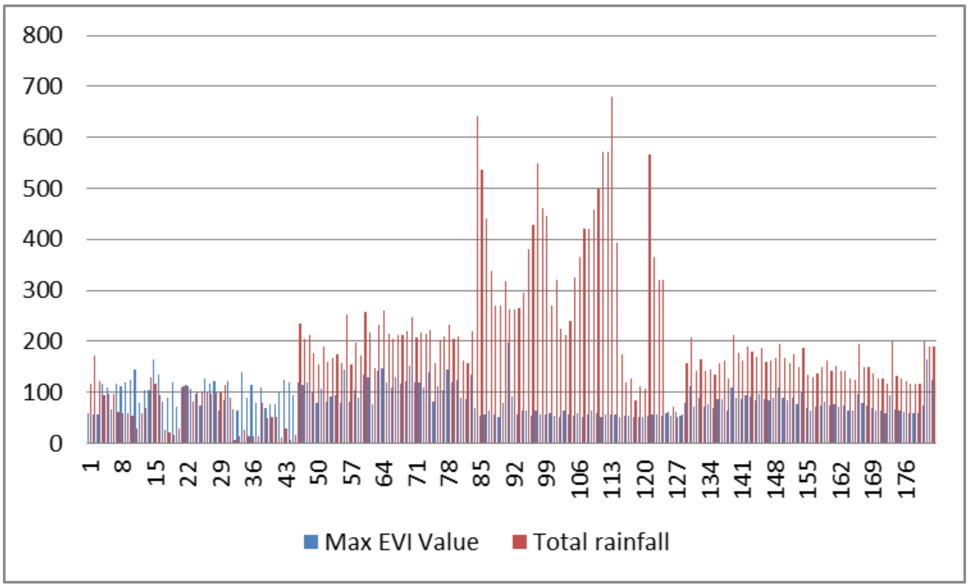


Figure 4.11: Maximum EVI values (blue bars) and Total Rainfall (Pink bars) during the summer 2005.

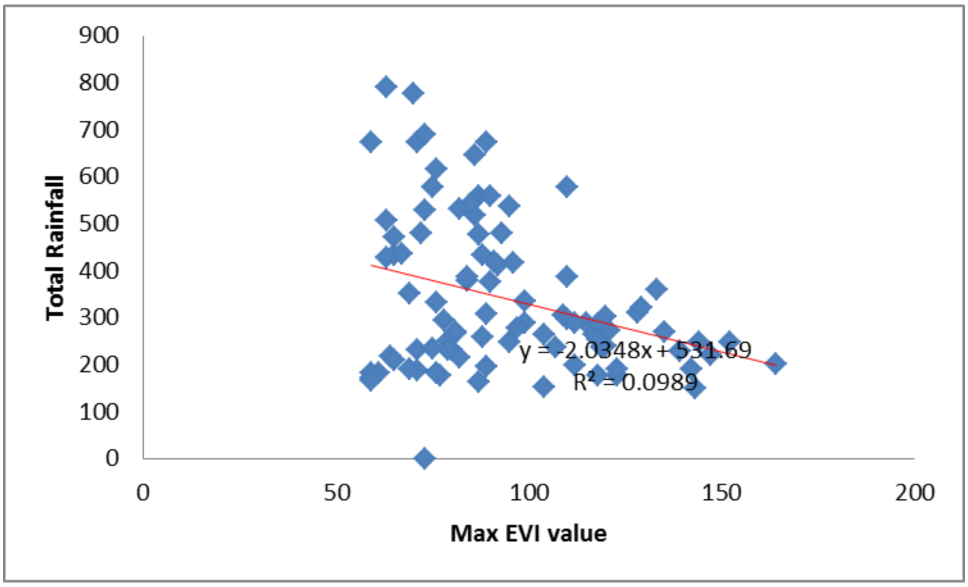


Figure 4.12: Correlation between maximum EVI and Rainfall during the summer 2005.

Figure 4.10 shows Desert Locust breeding in Sudan during summer 2005. Darfur states are considered as the potential breeding sites, and they accommodate the largest number of DL during the season. However, there were fewer DL seen in the other states. The EVI image indicated the high abundance of vegetation resources in Darfur States and Northern Kordofan and patches in the others states. Rainfall estimation varied during the season ranging from low level (200 – less 300 mm), medium (300 – less 400 mm) to high (400 – less 800) (See figure 4.11). Rainfall was associated with the maximum value with a small positive correlation that is shown in figure (4.12) where R2 =0.0989 so R = 0.1344. This means that if the rainfall increased to a very high rate, vegetation also increased at a small rate. During the mentioned season, results from the map figure 4.10 showed intensive survey activities in all DL summer breeding zones of Sudan. Much of the detected locusts were seen in Darfur states where resources were more readily available than the other states. (FAO 2005a) reported that early seasonal rains fell at times in Darfur states, where vegetation became green and, the ecological conditions were drier than in the other states. The situation attracted several circuit swarms to reach the green areas coming from Chad crossing the borders. As stated by Symmons and Cressman (2001) in the literature review, locust are able to locate areas of vegetation on which they land, even where these occur only as a few isolated patches, and yet how they do this is still not known. Therefore, as the season progressed, DL development occurred and many hopper bands and immature insects were controlled, mainly in west and North Darfur and in the Border of Chad/Sudan. Furthermore, some escaped swarms were seen past the central states of Sudan and lastly they were dispersed in the border of Sudan and Ethiopia. It is thus clear that rainfall played the major role in promoting early growth of vegetation that contained the circuited swarm, which generated extra outbreaks during the season and, that was why a small correlation was found. Van Huis (2006) states that, frequency of the rains and the duration of the rainy season allow two and a partially third generation of the desert locust to breed, at a higher rate of multiplication than normal. This is either because of more egg and/or greater survival occurrence.

4.2.5. Winter 2005

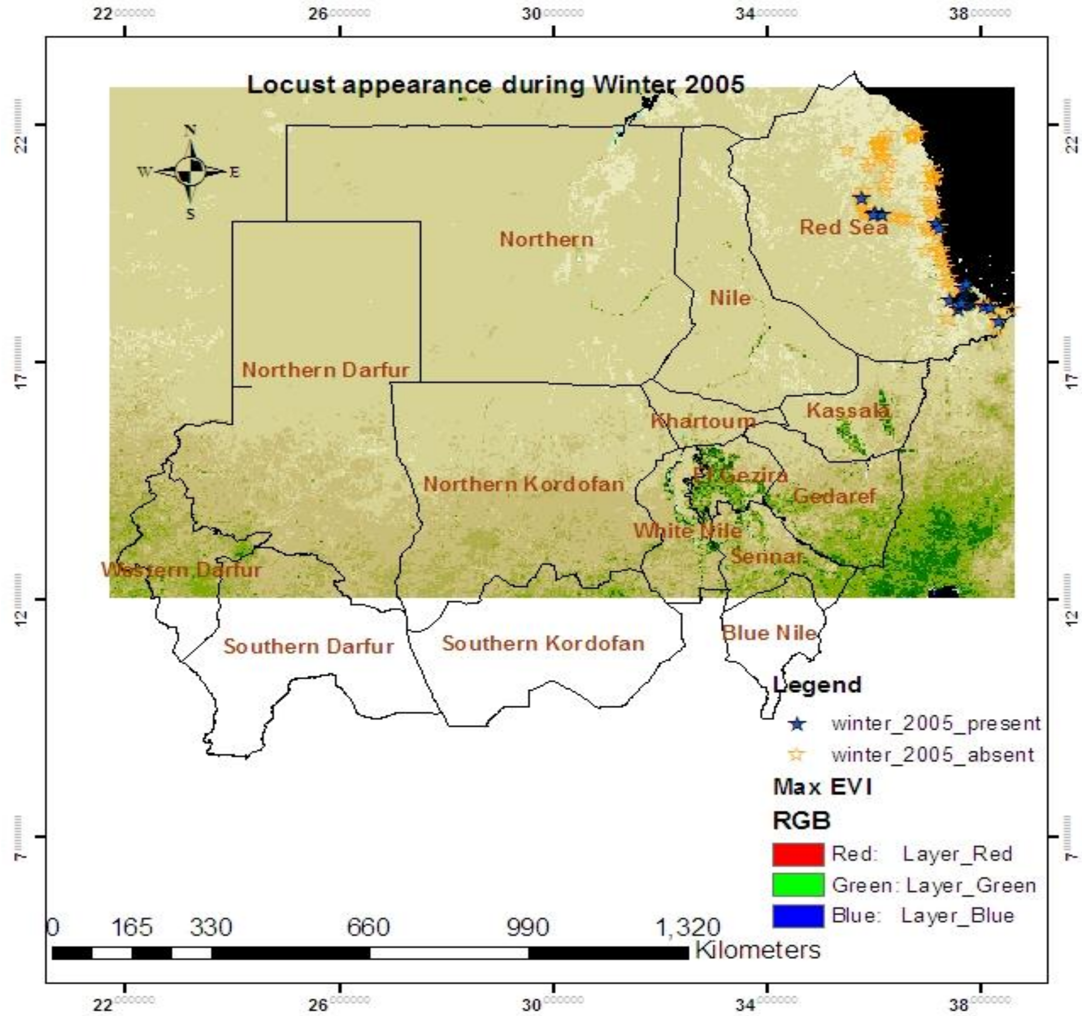


Figure 4.13: Showing vegetation abundance acquired as maximum MODIS EVI satellite image as composite of 2nd decade of December and Locust infestation during winter 2005, the blue stars symbolizing the presence of Desert Locusts and the orange ones their absence.

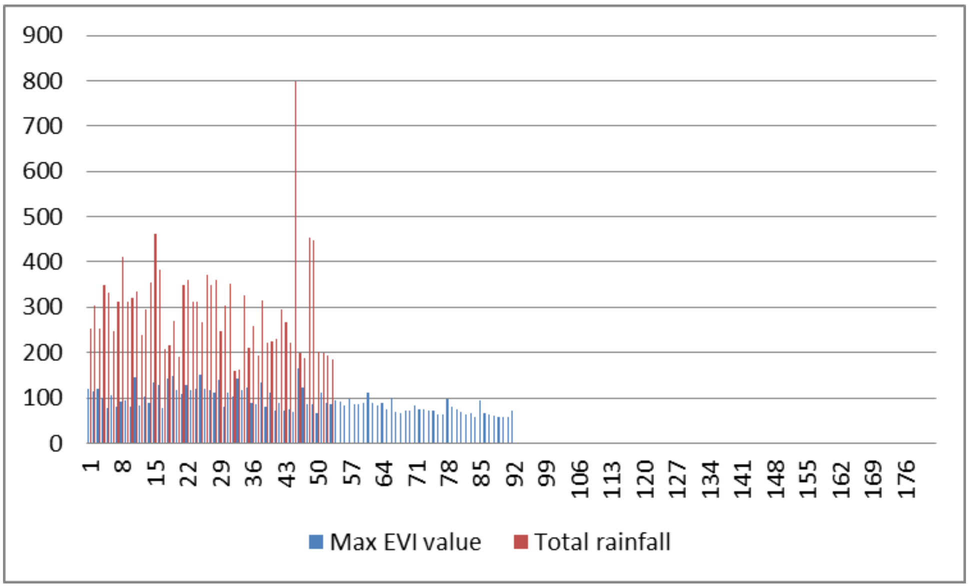


Figure 4.14: Maximum EVI values (blue bars) and Total Rainfall (Pink bars) during the season winter 2005.

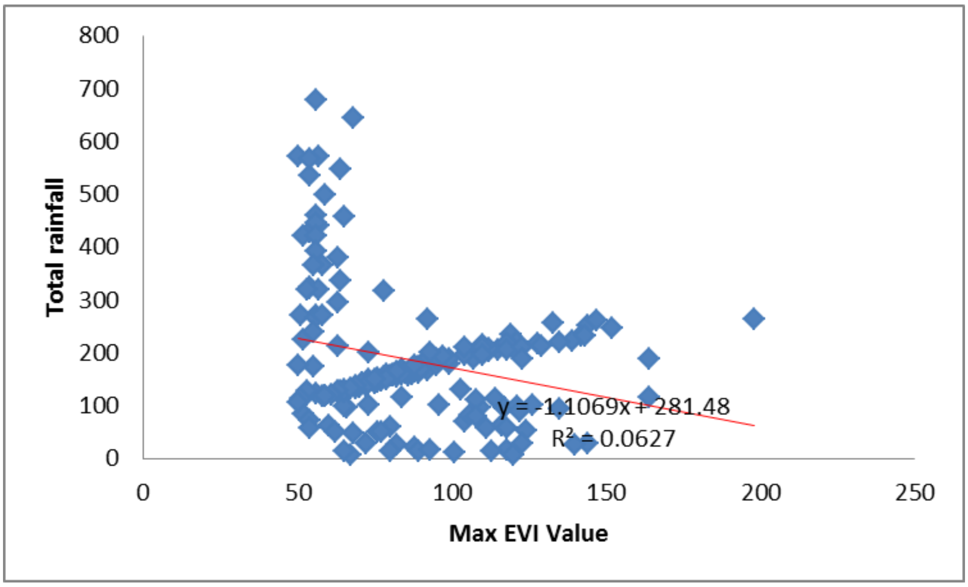


Figure 4.15: Correlation between maximum EVI and Rainfall during the winter season 2005.

During winter 2005, Desert Locust operations were conducted only in the Red Sea state, where Locust were detected in the southern part of the coast in Toker Delta, central coastal plain and in between the areas of the Red Sea Hills as shown in map Figure (4.13). However, there were no surveys conducted in other parts of Sudan during the same period. It was very difficult to discriminate the vegetative areas from the bare soil within the affected areas from the EVI satellite image, but the extracted data shown in figure (4.14) indicated the availability of vegetation varied in the magnitude from low to higher than 100 of EVI values. As well as rainfall amount which fluctuated in the amount from very low at less than 100 mm, medium above 200 mm to very high amounts in some observation points, and reached 600 to less than 700mm. A positive medium correlation was shown in figure (4.15), and indicated that a high increase of rainfall automatically corresponded to medium growth of vegetation.

As mentioned in the methodology chapter, Toker Delta habitat is a cultivated area and consists of fine silt soils that are nurtured by floods, arising from rainfall in the Red sea hills and Eritrean highlands that flow down to the Toker delta (USAID, 1995). The advantage of this area is that vegetation growth depends only partially on direct rainfall, because the foods normally promote germination of the plants. However, rainfall is the most important requirement for the Desert Locust breeding, because it orients the necessary environmental conditions for the breeding, development and multiplication (Suliman, 2002). During the winter of 2005 rainfall was reported between Toker Delta and Eritrean borders and, due to the event, small scale breeding of Desert Locust was reported to have commenced in the area. Rainfall was reported to have occurred and mainly in Toker Delta scattered hoppers and solitary locust individuals were reported (FAO, 2005 b). Maximum EVI image (figure 4.15) showed less greenness in the winter breeding areas that might be due to patterns of growth. It did allow the captured image to discriminate between the bare soil and the low vegetation growth, and as mentioned in the previous chapters this is one of MODIS limitations, where vegetation is present but not indicated on the corresponding acquired images, and this occurs in parts of Desert Locust recession areas (Cressman and Hoson, 2009). The positive relationships that were found between the rainfall and EVI value indicated the availability of the vegetative cover so far.

4.3. Statistical Analysis

4.3.1. Rainfall and Vegetation Patterns during the Study Years

Constants	Year 2003		Year 2004		Year 2005	
	Summer	Winter	Summer	Winter	Summer	Winter
Max EVI values	-	-	-	□**	-	□**
Min EVI values	□**	-	□**	□**	□**	-
Total rainfall	□**	-	-	-	□**	□**

Table 4.1: shows the relationship between the response variables (presence or absence of the locust) and the predictor variables (Max EVI, Min EVI, and Total rainfall), the analysis of binary logistic regression model carried out in Minitab software. The stars indicated the significant relationship between the tested variables during the specific season. All the obtained results are shown in the appendices (1).

The binary logistic regression model is used for testing the relationship between response variables and predictors, as described in (Table 4.1). The relationship is estimated by looking at p- value of the analysis, which indicates a significant relationship when the value is less than 0.05, which means that the model does not describe the data well, so the null hypothesis of data fitting the model can be rejected (Erhardt, 2011). During summer 2003, a significant relationship was found between the presence of the Desert Locust and minimum EVI values, which indicated a very low volume vegetation cover or patchy vegetation which might have promoted the growth of and development of the DL with a similar relationship that was found with total rainfall estimates. This also indicated that vegetation cover might contain the locust while it was green and enforce locust to move away to the complementary areas or to disappear from when it dried, because the trend of the vegetation normally affects the availability of the Desert Locust. Collett et al. (1998), Despland et al. (2000), Despland and Simpson (2000), and Despland et al. (2004) all claim that on the scale of individual plants, vegetation distribution influences grangerisation of locust populations: in a fragmented habitat with multiple dispersed patches, locusts remain solitary and the formation of outbreaks is inhibited. It is noteworthy that, there was no data tested for winter 2003, so no results were obtained. In summer 2004 a significant relationship was found only with minimum EVI value, but during winter of the same year both maximum and minimum EVI value showed the significant relationship with presence of the Desert locust, and no relation to the rainfall estimates were found. Summer 2005 showed a significant relationship between the response variable with EVI and total rainfall. However, the maximum EVI, which indicates the availability of the green vegetation cover during the season and the total rainfall, observed significant relationships during winter 2005. Despland, et al., (2004) state that, the vegetation contraction and locust concentration depend on where rain falls, and plays a significant role in determining whether a growing locust population will remain solitary and disperse, or grangerised and form swarms. Each of the tested seasons is influenced by different climatic conditions so the tested variable observed in different trends varies from one year to another. Therefore, the desert locust situation is also affected accordingly. Therefore, due to the works of the ecological process the outbreak of the Desert Locust differ between scales, according to the vegetation distribution.

4.3.2 Comparison between Maximum Vegetation Growth (MAX EVI) and Rainfall Estimate in between the Study Years

	2003 versus 2004		**2004 versus 2005**		**2003 versus 2005**	
	t- value	***P- value***	***t- value***	***P- value***	***t- value***	***P- value***
Max EVI	-4.31	<0.0000>	0.47	0.636	-4.98	<0.0000>
Rainfall	7.92	<0.0000>	-0.56	0.575	-12.92	<0.0000>

Table 4.2: Shows the comparisons of two t –test results for maximum EVI and rainfall, and that indicates whether a year might accommodate more resources, which promote higher chances for Desert Locust breeding. All tables of the analysis are attached in the appendices (2)

The t-value for both maximum EVI, total rainfall, - 4.31, 7.92 respectively, and their p-values <0.0000> (see table 4.2) showed that the null hypothesis of the two variables could be rejected, and instead concluded that there was a significant difference between them. Therefore, the assumption might indicate that EVI and rainfall were much more in 2003 than

2004. On the other hand, non-significant relationships showed in the year 2004 versus 2005, the null hypothesis cannot reject, and there was no significant difference obtained from the tested variables. So far, the year 2003 versus 2005 t test showed a significant difference from looking at t value and p-value as shown in the mentioned table. This means there was a difference in EVI and rainfall in the tested variables and 2003 might contain more vegetation and rainfall than 2005.

The principle of driving spectral profiles of indices from measurement at two (or more) wavelengths is widely adopted, especially in the use of vegetation indices (VI) for studying vegetation cover (Silreira, et al, 2008). On the other hand, (Dinku, et al., 2009) stated that rainfall estimates satellites have positive skills in detecting rainfall, but the high false-alarm decreases the detection ratios. However, the wet regions performances are much better than the drier parts. They also argue that, there is no single product that stood out as having the best or the worst performance consistently across sub regions. Local calibration, using locally available rain gauge data or PR estimates, and blending satellite products with locally available rain gauge measurements may help to alleviate the poor performance of satellite estimates. Results of this study proved the ability of using data extracted from remote sensing images acquired for MODIS EVI, and rainfall estimates (FRE) for monitoring vegetation biomass and, estimating rainfall respectively on different scales.

Chapter Five

Chapter 5

Conclusion and Recommendations

5.1. Conclusion

Desert Locust situations were seen varied at infestation pattern during the study period, because of many factors which controlled the development of the insects. Rainfall amount and vegetation status were remained major factors that orient Desert Locust development and multiplication. In addition to, the other factors such as topography and temperature. Largely vegetation structures during summer seasons depend on the rainfall amount and, that was approved by the remarkable greenness during year 2003 in almost all DL summer breeding areas of Sudan, as well as Northern Kordofan during year 2004 and, Darfur and Northern Kordofan states during year 2005. In the summer breeding areas previously mentioned, the acquired MODIS EVI satellite images reflected a quite good greenness of the vegetation cover, also the rainfall estimates (RFE) images showed amount of a reasonable rainfall in the same areas, when spectral profile were extracted by using ERDAS IMAGINE software. large areas that received sufficient rainfall amount and had produced adequate food supply, had initiated the Desert Locust outbreaks , either by promoting the local development and breeding of Locust or by attracting the uncontrolled locust groups to the prevailing favourable conditions, as that had occurred in River Nile state during summer 2003. All summer seasons during the study period received relatively good rainfall, accordingly DL formed local breeding in different areas varies according season pattern. On the other hand, during 2005, DL outbreak formation occurred in Chad and had migrated towards Sudan. That had severely affected the local breeding of DL and increased the infestation scale in Darfur, to extend that some of the swarms escaped from control and travelled through the country until reached Ethiopia. That situation might strongly confirm the importance of joining borders survey between Sudan and Chad, during successive breeding of Desert Locust years, although traditionally it was not undertaken before, but possible.

Desert Locust infestation during winter seasons along study period showed unusually patterns, that mainly due to the influence of uncontrolled locust groups that escaped from the summer zones towards the winter areas, as well as the invasions of the DL to the green area . During winter 2004 river Nile and the tributaries were invaded from the summer breeding zone. Moreover, DL invasions during the same period which arrived from Egypt to in land of

Sudan had increased frequencies of the infestation during the season. MODIS EVI was very poor in detecting the green vegetation in the winter breeding zone. Winter seasons during the study periods accommodated poor vegetation cover and most of the green areas concentrated in Toker Delta and fewer green patchy areas in other areas in the zone. However, most of the outbreaks that detected during winter seasons had formed as result of local development and breeding of the Desert Locust , because the plantations in Toker Delta remain green for longer period and could supply adequate food resources to the insects. But MODIS EVI showed only image of dense green areas and failed to detect areas with low scattered vegetation.

From the analysis of the result, both MODIS EVI and RFE found to have limitations, which appeared as how much these satellite images could be able to give an accurate estimate that explains the real situation in the field. MODIS EVI is of a lower spatial resolution, but higher resolution images are needed for monitoring of DL habitat. High resolution images are useful especially in monitoring the inaccessible areas such as mines areas or insecurity and crisis areas where suitable habitat could prevail and lead to DL breeding, in such areas of Darfur state and apart of Northern Kordofan. Concerning the rainfall estimate (FRE) images the best method of alleviating their performances is blending satellite products with locally available rain gauge measurements.

Other limitations found in this study was that firstly; FAO Desert Locust historical data spreadsheet contained very detailed information, so that the page tended to be very large, Therefore, some modifications were needed to be done to convert the spreadsheet to shapefiles in order to be used in ARC GIS. Secondly, in the rainfall estimate satellite image after the layers are stuck in ERDAS Imagine, areas of no rainfall events turned to be dark black in the final image, so it was not possible for the training point data to be seen, so the spectral profile was only obtained from rainfall event areas.

5.2. Recommendations

GIS and remote sensing technologies had been used for more than decade in the domain of the Desert Locust. Surveillance of habitats and monitoring, as well as guiding survey and control teams requires a detailed description of the situation in the field. Therefore, the following recommendation and suggestions would be useful for sustaining and improving strategies of Desert Locust management:

- Continuous training of survey and control personnels is crucial matter, for raising the awareness and performances for collecting highly accurate data from the suitable sites in the fields, also personnels of the information and forecasting should be trained very well on how to use GIS and remote sensing technology and internet access.
- Experts, researchers and DL concerned bodies should search for remote sensing products of highly spatial and temporal resolution, which allow detecting a very low volume of vegetation growth, also for estimating precipitation by using image of high precision in estimating rainfalls.
- Small meteorological units are needed to be installed in the seasonal stations, for measuring climate factors such as; rainfalls, temperature degrees, wind speed and direction and relative humidity. That is because satellite images are always not reflecting the real situation in the fields, so they should be incorporated with field data for further analysis and better understanding of the prevailing ecological conditions.
- A need for studies of habitat classification and mapping to Desert Locust according to their food preference, by using capabilities of remote sensing techniques, is quite important issue that will facilitate detecting the potential breeding areas, with fewer amounts of resources and efforts as well as time.
- Joint border surveys between the neighbouring countries should be implemented, during good rainy seasons and the start of DL outbreaks, because that will facilitate limiting of locust immigration in between. For example between Sudan and Tchad, Sudan with Egypt.

6. References

Abdalla, O, M. (2004). Ecological Field Studies on Population Dynamics of the Solitary Desert Locust(Schistocerca *gregaria*, Forskal).(Acrididae: Orthoptera). PHD thesis, University of Khartoum, Sudan.118pp.

Anyamba, A., Small, J., Tucker, C.J., Cressman, K., Love, T.B., Linthicum, K. (2005). Remote sensing of eco-climatic conditions associated with the 2004 Desert Locust Outbreak in Northwest and Sahelian Africa. In Proceedings of Pecora 16 Symposium - Global Priorities in Land Remote Sensing, September 23-27, 2005, Sioux Falls, South Dakota.

Barston, A. G., A. Kumar, L. Goddard, and M. P. Hoerling, (2005). Improving seasonal prediction practices through attribution of climate variability. *Bulletin of the American Meteorological Society* . 86:59–72.

Bennett. L. V. (1976). The development and termination of the 1968 plague of the desert locust. *Bulletin Entomological Research* 66:511-551.

Bernardi. M,. (2001).Linkages between FAO agroclimatic data resources and the development of GIS models for control of vector-borne diseases. *Acta Trop.* **79** pp. 21–34.

Bower, K.M. (2011). The Paired T-Test Using MINITAB. Scientific computing and Instrumentation. http://www.minitab.com/uploadedFiles/Shared_Resources/Documents/Articles/paired_t_test.pdf. Accessed on 20/09/2011.

Campbell, J. C. (2006). Introduction to remote sensing (4th ed.). New York: Guilford Press.

Ceccato, P., F. Veroustraete and E. Bartholomé.(2004). Operational early warning system using SPOTVEGETATION and TERRA-MODIS to predict Desert Locust outbreaks. *proceedings of the 2nd International SPOT-VEGETATION users conference* (Antwerp, . Luxembourg, Office for Official Publications of the European communities.

Ceccato, P., K. Cressman, A. Giannini, and S. Trzaska, (2007). The desert locust upsurge in West Africa (2003-2005): Information on The Desert Locust Early Warning System, and the prospects for seasonal climate forecasting. Int. *J. Pest Manage.*, 53 (1), 7-13.

Cherlet, M., & Di Gregorio, A. (1993). Calibration and integrated modelling of remote sensing data for Desert locust habitat monitoring (RSC Series 64). Rome, Italy: FAO.

Collett, M., E. Despland, S.J. Simpson, D.C. Krakauer (1998). Spatial scales of desert locust gregarization. *Ecology 95*:13052-13055.

Cressman, K. (1996). Current methods of desert locust forecasting at FAO. */ OEPP/EPPO Bull.* 26: 567 /576.

Cressman, K. (1998) . Monitoring Desert Locusts in the Middle East: An Overview. *Transformations of Middle Eastern Natural Environments: Legacies and Lessons* held

28 October– 1 November 1997 at Yale University.

Cressman, K. (2001). Desert locust guidelines: 2. Survey. Rome, FAO-UN. 2nd Edition. www.fao.org/ag/locusts/common/ecg/347_en_DLG2e.pdf. Accessed on 15/08/2011.

Cressman, K. (2008). The use of new technologies in Desert Locust early warning. *Outlooks on Pest Management*, April: 55-59.FAO, 2011.

Cressman, K and Hodson. D.(2009).Surveillance, information sharing and early warning systems for transboundary plant pests diseases: the FAO experience *Arab journal of plant protection.* Vol. 27.2.p 226-232.

DAFF (2011). Monitoring and Forecasting Locust Populations. Australian Government. http://www.daff.gov.au/animal-plant-health/locusts/aplc-activities/monitoring . Accessed on 10/8/2011.

Despland, E., Collett, M. and Simpson, S.(2000). Small-scale processes in desert locust swarm formation: how vegetation patterns influence gregarisation. *Oikos* 88: 652 /66.

Despland, E. and Simpson, S. (2000). Small-scale vegetation patterns in the parental environment influence the phase state of hatchlings of the desert locust. *Physiol. Entomol.* 25: 1 /9.

Despland, E., J. Rosenberg, S.J. Simpson (2004). Landscape structure and locust swarming: a satellite's eye view. *Ecography 27*:381-391.

Dinku, T., P. Ceccato, K. Cressman, and S. J. Connor, (2010). Evaluating Detection Skills of Satellite Rainfall Estimates over Desert Locust Recession Regions.

Journal of Applied Meteorology & Climatology.vol. 49, pp.1322-1332.

Dutta .D, Bhatawdekar. S, Chandrasekharan . B, Sharma J.R, Adiga. S, Duncan .W and McCardle. A .(2008). Desert Locust Monitoring System – Semote Sensing and GIS based approach. *Satellite Remote Sensing and GIS Applications in Agricultural Meteorology* .pp. 401-423.

El-Tom, H.A. (1993). Strategies and Resources for Desert Locust Control in Sudan. In: Desert Locust Control with the Existing Techniques. Proceedings of the Seminar held in Wageningen, the Netherlands, 6-11 December.

Emana. B, (2002). Socio-economics of Desert Locust Control in Sudan. A Micro Level Case Study . Final Draft Report. http://crc-empres.faorne.net/public/Document/Document-2005925151457_Ecomom%20Study_Sudan%20Case-Bezabih_2002.pdf. Accessed on 17/8/2011.

Ellis, P.E., Ashall, C., (1957). Field studies on diurnal behaviour, movement and aggregation in the desert locust (Schistocerca gregaria Forska˚ l). Anti-Locust Bulletin 25, 1–94.

Erhardt , E (2011). Lab 12 Logistic regression, .Stat. 538- Biostatistics 1. http://statacumen.com/old/courses/stat538/stat538_lab12.pdf. Accessed 12/10/2011).

Eriksson. H. (2008). Effects on Non-Target Organisms of Insecticides Used to Control Desert Locust, *Schistocerca gregaria.* Environmental Impact in Ecologically Sensitive Areas. PHD theis. Swedish University of Agricultural Sciences. Uppsala. http://pub.epsilon.slu.se/1739/1/Eriksson_Helena_2008.pdf

Evrendilek, F., & Gulbeyaz, O. (2008). Deriving vegetation dynamics of natural terrestrial ecosystems from MODIS NDVI/EVI data over Turkey. *Sensors, 8*, 5270-5302.

FAO (2003).Locust watch. Desert Locust Archives 2003. *Desert Locust Bulletin (*297-301) (June-October).

FAO (2004 a).Locust watch. Desert Locust Archives 2003. *Desert Locust Bulletin (*309-313). (June-October).

FAO (2004 b).Locust watch. Desert Locust Archives 2003. *Desert Locust Bulletin (*314-318) (November,2004 –March, 2005).

FAO (2005 a).Locust watch. Desert Locust Archives 2003. *Desert Locust Bulletin (*321-325) ((June-October).

FAO (2005 b).Locust watch. Desert Locust Archives 2003. *Desert Locust Bulletin (*326-327) (November,2005 – December, 2005).

FAO , (2007) Preparedness to Prevent Desert Locust Plagues in the Central Region: An Historical Review. FAO Desert Locust Technical Series, AGP/DL/TS/35, Food and Agriculture Organization, 129 pp.

FAO,(2011). Locust watch. Desert Locust. Satellite information for locust forecasting. Food and Agriculture Organization. http://www.fao.org/ag/locusts/en/activ/DLIS/satel/index.html. Accessed on 08/07/2011.

Ghaemian, M. (2002). Improved survey methods for gregarious or gregarizing hopper patches of the Desert Locust Msc Thesis, Imperial College of Science, Technology and Medicine, Silwood Park, Ascot, U.K.

Heywood, Ian, Cornelus, Sarah and Carver, Steve. (2002), *An Introduction to Geographical Information Systems*. 2nd ed., Prentice Hall.

Heywood, Ian, Cornelus, Sarah and Carver, Steve. (2006), *An Introduction to Geographical Information Systems*. 3rd ed., Prentice Hall.

Hielkema, J.U., (1977). Application of Landsat data in desert locust survey and control. AGP: LCC/77/11, FAO, Rome, Italy.

Hielkema, J.U., 1980. Remote sensing techniques and methodologies for monitoring ecological conditions for desert locust population development. Final Technical Report CGP/INT/349/USA, FAO, Rome, Italy.

Hielkema, J. U., Roffey, J. And Tucker, C. J. (1986). Assessment of the ecological conditions associated with the 1980/81 desert locust plague upsurge in West Africa using the environmental satellite data. *International Journal of Remote Sensing,* **7** (11), 1609-1622.

Hielkema, J. U., and F. L. Sunders, (1994). Operational use of environmental satellite remote sensing and satellite communications technology for global food security and locust control by FAO: The ARTEMIS and DIANA system. *Acta Astronaut*., 32, 603-616.

Holt. J. and Cheke, R.A., 1996. Models of desert locust phase changes. *Ecol. Modelling* **91**, pp. 131–137.Pedgley, D. E. (1981). Desert locust forecasting manual. Vol. 1. London:

HMSO, 268 PP.

Huete. A, Justice. C, Liu. H,(1994). Development of vegetation and soil indices for MODIS-EOS. *Remote Sensing of Environment*. Vol 49.3.pp 224-234.

Huete, A., Justice, C., and Leeuwen, W.,(1999). MODIS vegetation index (MOD 13). Algorithm theoretical basis document ATBD13. Electronic document: http://modis.gsfc.nasa.gov/data/atbd/atbd_mod13.pdf.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G.(2002).Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote sensing of Environment*, 83, 195−213.

Ibrahim, E. M ., (2006). A method for detection of desert locust, *Shistocerca gregaria* (Forskal) and estimation of the infested areas. M.Sc Thesis. http://crc-empres.org/public/Document/Document-201012453920_M.Sc%20Essam.PDF. Accessed on 12/9/2011.

JI, R. and XIE, B.Y , (2004). Use of MODIS data to monitor the oriental migratory locust plague. *Agriculture, Ecosystems and Environment*, 104, pp. 615–620.

Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie, (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeor*., 5, 487-503.

Kennedy, J.S., (1939). The behaviour of the desert locust (Schistocerca gregaria (Forsk.)) (Orthopt.) in an outbreak centre. Transactions of the Royal Entomological Society of London 89, 385–542.

Krall, S., Peveling, R. and Ba Diallo, D. [eds.] (1997). *New Strategies in Locust Control*. Birkhauser, Basel, Switzerland.

Magor, J.I. (1994). Locust glossary. Pages 119-127 in Huis A van (ed) Desert Locust Control with exiting Techniques: an Evaluation of Strategies. Proceedings of the Seminar held in Wageningen, The Netherlands, 6-11 December 1993., Wageningen Agriculture University, 132 pp.

Magor, J.I., Lecoq, M., Hunter, D.M. (2008). Preventive Control and Desert Locust Plagues. *Crop Protection* 27, 1527-1533.

Mahmoud. O. R, (2010). Application of Geographical Information Systems and Remote Sensing in Estimating the Likely Breeding and Infested areas of the Desert Locust (*Schistocerca gregaria,* Forskal). MSc thesis. Faculty of Development and Society. Sheffield Hallam University. UK.

Maywald, G . F . , Timmers P ., Bottomly . W and R . W. Sutherst .,(1999). Dymex: Modelling Natural Systems. Professional Model Simulator User ' s Guide. Canberra, Australia: CSIRO Publishing.

Maeno. K, Tanaka. S.(2011). Phase-specific responses to different qualities of food in the desert locust, Schistocerca gregaria: Developmental, morphological and reproductive characteristics, *Journal of Insect Physiology*, Volume 57: 4, PP514-520.

Maxwell - Darling, R.C. (1936). The outbreak Centres of *Schistocerca gregaria* Forskal. On the Red Sea coast of the Sudan. *Bull. ent. Res*. 27: 37 – 66.

Meteo Consult (1995). *Desert Locust migration model*. Meteo Consult B.V., Wageningen, The Netherlands.

Neteler, M. (2004). MODIS time series remote sensing for epidemiological modelling. In *International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences*, Hanoi, Vietnam, http://www.ipk.bv.tum.de/3dugi/journals_website/Geoinformatics/viewpaper.pdf.

Pedgley, D.E., 1973. Testing feasibility of detecting locust breeding sites by satellite. Final Report to NASA-1, Experiment, COPR, London.

Pedgley, D., (ed.) (1981). Desert Locust Forecasting Manual . Centre for Overseas Pest Research. *London HMSO, UK*.Vol.1., 268pp.

Pekel J.-F. , Ceccato. P., Vancutsem .C., Cressman .K. ,Vanbogaert E., Defourny P., *(2010).* Development and Application of Multitemporal colorimetric transformation to monitor vegetation in the desert Locust habitat, *IEEE Journal of* selected topics in applied earth observations and remote sensing.

Pinker, R.T., Zhao, Y., Akoshile, C., Janowiak, J. and Arkin, P. (2006). Diurnal and seasonal

Variability of rainfall in the sub-Sahel as seen from observations, satellites and a numerical model. *Geophysical Research Letters 33(7): pp 0094-8276.*

Popov, G.B. (1975). Report of the Special Survey of the Northern Libyan Arab Republic – November 1974. *Commission for Desert Locust Control in Northwest Africa. Special Survey Report no.* NWA/DL/SS/1. Rome: Food and Agriculture Organization of the United Nations.

Rainey R. C. (1963) Meteorology and the migration of desert locust: applications of synoptic meteorology in locust control. *Anti-locust memoir no* **7**. Also as WMO Technical notes 54: same as WMO no **138**. TP 64.

Ripper, W. E, and George, L. (1965). Cotton Pest of the Sudan, Their Habits and Control. Oxford: *Blackwell Scientific Publications*.

Roffey, J., Popov, G., (1968). Environmental and behavioural processes in a desert locust outbreak. Nature 219, 446–450.

Roffey, J. (1982). The Desert Locust upsurge and its termination 1977-79. In Field Research station-Technical Series. FAO Report AGP/DL/TS/23,iii-iv + 1-47.

Rome (1999). A Joint Survey of the Winter Breeding Areas of the Desert Locust on the Red Sea Coast of Sudan. Food and Agricultural organization http://www.fao.org/ag/locusts/en/publicat/meeting/topic/jointsur/864/documents_865.html. _Accessed on 18/09/2001.

Rosenberg, L.J. (2000) 'Information Systems for Locust Forecasting'. In Cheke, R.A Rosenberf, L.J., Keiser, M.E. (eds) *Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa.* held 24–26 March 1999 at Plant Protection Research Institute, Pretoria, South Africa. Chatham: Natural Resources Institute, 165-171. http://www.icosamp.ecoport.org/archives/mpw/P17.pdf. Accessed on 24/09/2011.

Showler, A.T., (1997). Proaction: strategic framework for today's reality. In: Krall, S., Peveling, R., Ba Diallo, D. (Eds.), New Strategies in Locust Control. Switzerland, Birkha¨user, Basel, pp. 461–465.

Showler, A.T. (2002). A summary of control strategies for the desert locust, *Schistocerca gregaria* (Forskål)'. *Agriculture, Ecosystems and Environment* 90, 97-1-3.

Steedman, A. (Ed) (1990). *Locust handbook* (3rd ed.) Natural Resources Institute: London. Vi + 204 pp.

Suliman, K. (2005). Distribution of the Desert Locust (Schistocerca *gregaria*, Forskal). (Acrididae: Orthoptera), in relation to the herbage quality in the Red Sea of Sudan. MSc thesis, University of Khartoum. Sudan.

Sword, G. A., Lecoq. M, Simpson. S. J.(2010).Phase polyphenism and preventative locust management, *Journal of Insect Physiology*, Volume 56, Issue 8, PP 949-957.

Symmons PM, Cressman K.(2001). Desert Locust Guidelines. 1. Biology and Behaviour. 2nd ed. Rome: Food and Agriculture Organization of the United Nation.

http://www.fao.org/ag/locusts/oldsite/PDFs/DLG1e.pdf. Accessed on 2/8/20011.

Tappan, G. G., Moore, D. G., & Knausenberger, W. I. (1991). Monitoring grasshopper and locust habitats in Sahelian Africa using GIS and remote sensing technology. *International Journal of Geographical.*

Tucker, C.J., J.U. Hielkema and J. Roffey. (1985).The potential of satellite remote sensing of ecological conditions of survey and forecasting Desert Locust activity. Int. J. Remote Sensing, 6: 127-138.

Uvarov, B.P. (1957). The aridity factor in the ecology of desert locust and grasshoppers of the old world. *Arid Zone Research VIII*. Human and Animal Ecology Review of Research, UNESCO, Paris, France, pp. 164-198.

Uvarov, B, (1977). Grasshoppers and Locusts A hand book og General Acridology.(volume 2) COPR. Centre for Overseases Pest Research 613.

van Huis, A. ,(1994). Desert locust control with existing techniques: An evaluation of strategies. *Proceeding of the seminar held in Wageningen,* The Netherlands 6-11 December, 1993, Wageningen Agricultural University, The Netherlands, 132 pp.

Van Huis, A.,Cressman. K, and, Magor .J. I. (2007). Preventing desert locust plagues: Optimizing management interventions. *Entomol. Exp. Appl.*, 122, 191-214.

Wardhaugh, K., Ashour, Y., Ibrahim, A. O.; Khan, A. M. and Bassonbol, M. (1969). Experiments on incubation and hopper development periods of the Desert

Locust, *Schistocerca gregaria* (Forskal) in Saudi Arabia. Anti – locust Bull.45:38pp.

Wilps. H. (1997) Ecology of *S. gregaria*. In: Krall S, Peveling R, Ba Diallo D (eds.) New strategies in locust control. Birkhäuser Verlag, Basle, Switzerland.

Woldewahid, G. (2003). Habitats and spatial pattern of solitarious desert locusts (Schistocerca gregaria Forsk.) on the coastal plain of Sudan. PhD Thesis. Wageningen University. http://library.wur.nl/wda/dissertations/dis3509.pdf. Accessed on 30/07/2010.

Woldewahid, G., van der Werf, W., Sykora, K., Abate, T., Mostofa, B. & van Huis, A. (2007). Description of plant communities on the Red Sea coastal plain of Sudan. *Journal of Arid Environments 68*, 113-131.

Zhang, X., Sun, R., Zhang, B., & Tong, Q.X. (2008). Land cover classification of the North China Plain using MODIS_EVI time series. *Isprs Journal of Photogrammetry and Remote Sensing*, *63*, 476-484.

CRC-EMPRESS,(2010). Sudan. http://crcempres.org/Profiles.aspx?ty=p&O=8&id=27. Accessed on 25/07/2010.

ERDAS, (2009). Using Profile Tools. ftp://ftp.ecn.purdue.edu/jshan/86/help/html/hyperspectral/using_profile_tools.htm Accessed on 15/08/ 2011.

ERDAS, (2011). Question 9: Describe the function and the important of spectral, spatial and surface profile tools. http://www.scribd.com/doc/70395382/ERDAS-1. Accessed on 30/10/2011.

Minitab,(2011).http://www.minitab.com/uploadedFiles/Shared_Resources/Documents/Sample_Materials/TrainingTTest16EN.pdf. Accessed on 20/09/2011.

Latchininsky. A and Sivanpillai. R ,.(2010).Locust Habitat Monitoring and Risk Assessment Using Remote Sensing and GIS technologies. http://www.uwyo.edu/renewable/faculty-and staff/latchininsky/documents/2010%20Latchininsky%20Sivanpillai%20Springer.pdf

USAID, (1990). Supplemental Environmental Assessment (Sea) for USAID Funding of Locust or Grasshopper Pesticide Usage in Sudan http://pdf.usaid.gov/pdf_docs/PNABJ877.pdf. Accessed on 17/09/2011.

Appendices

Summer 2003

1.1 Binary Logistic Regression:

Dependent p/ versus Max EVI valu, Min EVI valu, ...

Link Function: Logit

Response Information

Variable	Value	Count	
Dependent p/a	1	31	(Event)
	0	33	
	Total	64	

Logistic Regression Table

					Odds	95% CI	
Predictor	Coef	SE Coef	Z	P	Ratio	Lower	Upper
Constant	-1.07842	2.32524	-0.46	**0.643**			
Max EVI values	-0.0497793	0.0276665	-1.80	0**.072**	0.95	0.90	1.00
Min EVI value	0.100501	0.0338420	2.97	0**.003**	1.11	1.03	1.18
Tatal Rainfall values	-0.0077869	0.0032842	-2.37	**0.018**	0.99	0.99	1.00

Log-Likelihood = -33.482

Test that all slopes are zero: G = 21.696, DF = 3, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	59.2692	60	0.502
Deviance	66.9640	60	0.250
Hosmer-Lemeshow	13.7234	8	0.089

Table of Observed and Expected Frequencies:

(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

	Group										
Value	1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	0	4	3	1	2	4	6	6	5	31
Exp	0.3	0.7	1.7	2.1	3.0	3.4	4.0	5.0	4.7	6.1	
0											
Obs	6	6	3	3	6	4	2	1	0	2	33
Exp	5.7	5.3	5.3	3.9	4.0	2.6	2.0	2.0	1.3	0.9	
Total	6	6	7	6	7	6	6	7	6	7	64

Measures of Association:

(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	827	80.8	Somers' D	0.62
Discordant	195	19.1	Goodman-Kruskal Gamma	0.62
Ties	1	0.1	Kendall's Tau-a	0.31

Total 1023 100.0

1.2 Two-Sample T-Test and CI: Max EVI values, Tatal Rainfall values

Two-sample T for Max EVI values vs Tatal Rainfall values

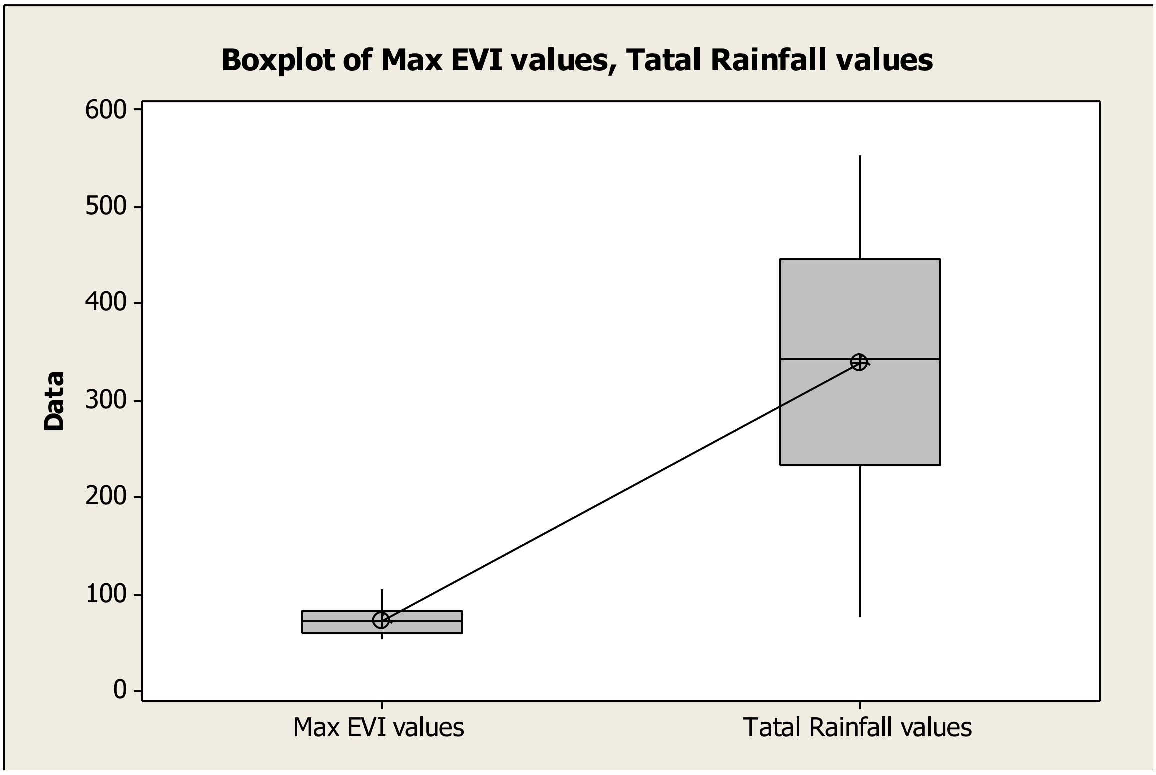
	N	Mean	StDev	SE Mean
Max EVI values	64	72.8	13.5	1.7
Tatal Rainfall values	64	339	136	17

Difference = mu (Max EVI values) - mu (Tatal Rainfall values)

Estimate for difference: -266.3

95% CI for difference: (-300.5, -232.1)

T-Test of difference = 0 (vs not =): T-Value = -15.55 P-Value = 0.000 DF = 64



2.1.1 Summer_2004

Binary Logistic Regression: Dependent p/ versus Max EVI valu, Min EVI valu, ...

Link Function: Logit

Response Information

Variable	Value	Count	
Dependent p/a	1	19	(Event)
	0	50	
	Total	69	

Logistic Regression Table

					Odds	95% CI	
Predictor	Coef	SE Coef	Z	P	Ratio	Lower	Upper
Constant	9.98080	3.48468	2.86	0.004			
Max EVI value	0.0240795	0.0203623	1.18	0.237	1.02	0.98	1.07
Min EVI value	-0.185270	0.0603203	-3.07	0.002	0.83	0.74	0.94
rainfall	-0.0004375	0.0034504	-0.13	0.899	1.00	0.99	1.01

Log-Likelihood = -30.426

Test that all slopes are zero: G = 20.364, DF = 3, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	52.9919	65	0.857
Deviance	60.8515	65	0.623
Hosmer-Lemeshow	4.4331	8	0.816

Table of Observed and Expected Frequencies:

(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

	Group										
Value	1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	0	0	1	1	4	2	3	4	4	19
Exp	0.0	0.1	0.4	0.8	1.3	1.9	2.6	3.2	3.9	4.8	
0											
Obs	6	7	7	6	6	3	5	4	3	3	50
Exp	6.0	6.9	6.6	6.2	5.7	5.1	4.4	3.8	3.1	2.2	
Total	6	7	7	7	7	7	7	7	7	7	69

Measures of Association:

(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	776	81.7	Somers' D	0.64
Discordant	171	18.0	Goodman-Kruskal Gamma	0.64
Ties	3	0.3	Kendall's Tau-a	0.26
Total	950	100.0		

2.1.2 Wintwr_2004:

Binary Logistic Regression: Dependent P/ versus EVI values, Min Evi valu, ...

Link Function: Logit

Response Information

Variable	Value	Count	
Dependent P/a	1	20	(Event)
	0	33	
	Total	53	

Logistic Regression Table

					Odds	95% CI	
Predictor	Coef	SE Coef	Z	P	Ratio	Lower	Upper
Constant	-17.1333	6.62263	-2.59	0.010			
EVI values	0.0537290	0.0200278	2.68	0.007	1.06	1.01	1.10
Min Evi values	0.143598	0.0710401	2.02	0.043	1.15	1.00	1.33
Total rainfall	0.0162190	0.0278528	0.58	0.560	1.02	0.96	1.07

Log-Likelihood = -6.423

Test that all slopes are zero: G = 57.406, DF = 3, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	15.7035	49	1.000
Deviance	12.8460	49	1.000
Hosmer-Lemeshow	5.1718	8	0.739

Table of Observed and Expected Frequencies:

(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

	Group										
Value	1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	0	0	0	0	0	5	4	5	6	20
Exp	0.0	0.0	0.0	0.1	0.1	0.3	3.7	4.8	5.0	6.0	
0											
Obs	5	5	5	6	5	5	1	1	0	0	33
Exp	5.0	5.0	5.0	5.9	4.9	4.7	2.3	0.2	0.0	0.0	
Total	5	5	5	6	5	5	6	5	5	6	53

Measures of Association:

(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	653	98.9	Somers' D	0.98
Discordant	7	1.1	Goodman-Kruskal Gamma	0.98
Ties	0	0.0	Kendall's Tau-a	0.47
Total	660	100.0		

2.2 Two-Sample T-Test and CI: Max EVI value, rainfall

Two-sample T for Max EVI value vs rainfall

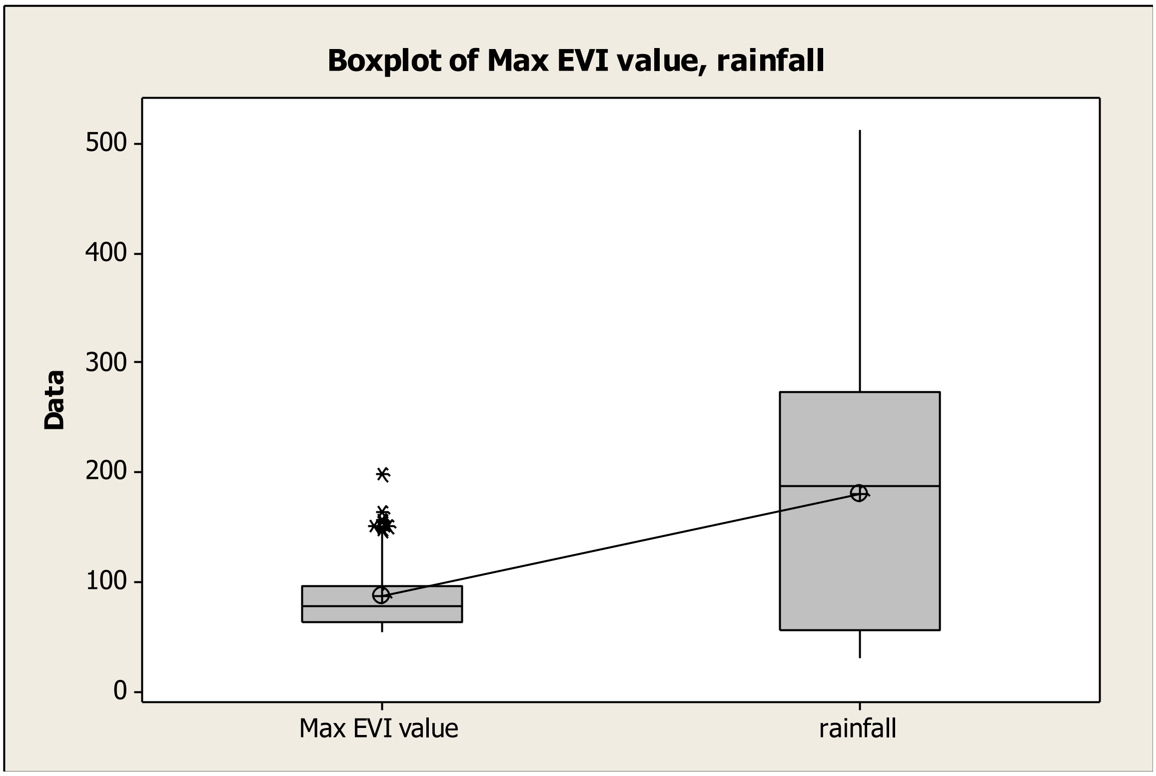
	N	Mean	StDev	SE Mean
Max EVI value	122	86.3	30.3	2.7
rainfall	122	181	129	12

Difference = mu (Max EVI value) - mu (rainfall)

Estimate for difference: -94.3

95% CI for difference: (-118.1, -70.5)

T-Test of difference = 0 (vs not =): T-Value = -7.84 P-Value = 0.000 DF = 134



Summer 2005

Binary Logistic Regression: Dependent P/ versus Max EVI Valu, Min EVI valu, ...

Link Function: Logit

Response Information

Variable	Value	Count	
Dependent P/A	1	45	(Event)
	0	45	
	Total	90	

Logistic Regression Table

Predictor	Coef	SE Coef	Z	P	Odds Ratio	95% CI Lower	Upper
Constant	-14.5432	4.88113	-2.98	0.003			
Max EVI Value	-0.0141844	0.0230856	-0.61	0.539	0.99	0.94	1.03
Min EVI values	0.296836	0.0994522	2.98	0.003	1.35	1.11	1.64
Total rainfall	-0.0261632	0.0081359	-3.22	0.001	0.97	0.96	0.99

Log-Likelihood = -11.516

Test that all slopes are zero: G = 101.734, DF = 3, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P
Pearson	28.4997	86	1.000
Deviance	23.0328	86	1.000

Hosmer-Lemeshow 3.3292 8 0.912

Table of Observed and Expected Frequencies:

(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

	Group										
Value	1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	0	0	1	2	6	9	9	9	9	45
Exp	0.0	0.0	0.0	0.3	2.0	7.1	8.8	8.9	9.0	9.0	
0											
Obs	9	9	9	8	7	3	0	0	0	0	45
Exp	9.0	9.0	9.0	8.7	7.0	1.9	0.2	0.1	0.0	0.0	
Total	9	9	9	9	9	9	9	9	9	9	90

Measures of Association:

(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	2002	98.9	Somers' D	0.98
Discordant	23	1.1	Goodman-Kruskal Gamma	0.98
Ties	0	0.0	Kendall's Tau-a	0.49
Total	2025	100.0		

Winter 2005:

Binary Logistic Regression: Dependent P/ versus Max EVI valu, Min EVI valu, ...

Link Function: Logit

Response Information

Variable	Value	Count	
Dependent P/A	1	38	(Event)
	0	54	
	Total	92	

Logistic Regression Table

					Odds	95% CI	
Predictor	Coef	SE Coef	Z	P	Ratio	Lower	Upper
Constant	-2.37550	1.82212	-1.30	0.192			
Max EVI value	0.111420	0.0340392	3.27	0.001	1.12	1.05	1.19
Min EVI value	-0.0745412	0.0458583	-1.63	0.104	0.93	0.85	1.02
Total rainfall	-0.0074161	0.0025930	-2.86	0.004	0.99	0.99	1.00

Log-Likelihood = -34.674

Test that all slopes are zero: G = 55.394, DF = 3, P-Value = 0.000

Goodness-of-Fit Tests

Method	Chi-Square	DF	P

Pearson	272.811	88	0.000
Deviance	69.348	88	0.929
Hosmer-Lemeshow	10.392	8	0.239

Table of Observed and Expected Frequencies:

(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

	Group										
Value	1	2	3	4	5	6	7	8	9	10	Total
1											
Obs	0	0	0	1	3	3	7	7	8	9	38
Exp	0.1	0.4	0.8	1.6	2.3	3.1	4.9	6.8	8.1	9.9	
0											
Obs	9	9	9	8	7	6	2	2	1	1	54
Exp	8.9	8.6	8.2	7.4	7.7	5.9	4.1	2.2	0.9	0.1	
Total	9	9	9	9	10	9	9	9	9	10	92

Measures of Association:

(Between the Response Variable and Predicted Probabilities)

Pairs	Number	Percent	Summary Measures	
Concordant	1899	92.5	Somers' D	0.85
Discordant	148	7.2	Goodman-Kruskal Gamma	0.86
Ties	5	0.2	Kendall's Tau-a	0.42
Total	2052	100.0		

Year 2005:

Two-Sample T-Test and CI: Max EVI Value, Total rainfall

Two-sample T for Max EVI Value vs Total rainfall

	N	Mean	StDev	SE Mean
Max EVI Value	182	87.0	28.9	2.1
Total rainfall	182	185	128	9.5

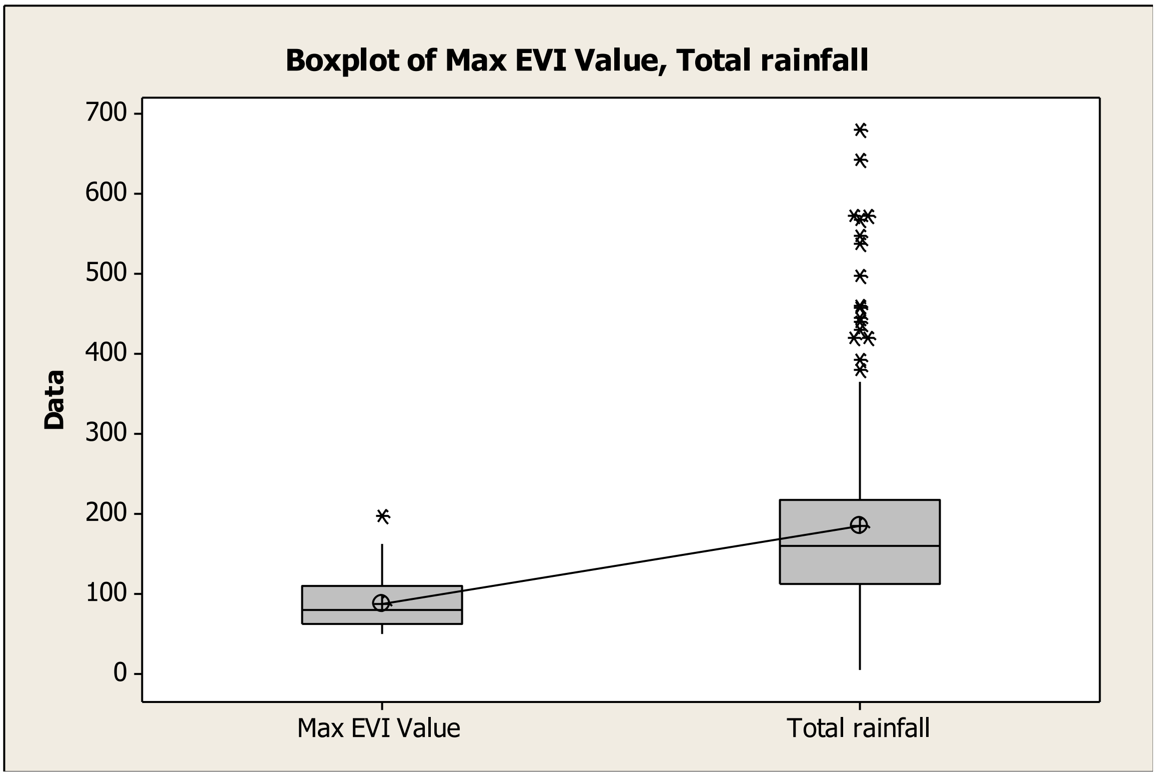
Difference = mu (Max EVI Value) - mu (Total rainfall)

Estimate for difference: -98.13

95% CI for difference: (-117.29, -78.97)

T-Test of difference = 0 (vs not =): T-Value = -10.10 P-Value = 0.000 DF = 199

Boxplot of Max EVI Value, Total rainfall


Boxplot of Max EVI Value, Total rainfall
Data
700
600
500
400
300
200
100
0
Max EVI Value
Total rainfall

Appendix 2

FAO Desert Locust survey and control form:

	(indicate appropriate information as required)						
1	**SURVEY STOP**	**1**	**2**	**3**	**4**	**5**	**6**
1-1	date						
1-2	name						
1-3	latitude (N)						
1-4	longitude (E or W)						
2	**ECOLOGY**						
2-1	area (ha) of survey						
2-2	habitat (wadi, plains, dunes, crops)						
2-3	date of last rain						
2-4	rain amount (mm, Low Moderate High, ?)	L M H ?	L M H ?	L M H ?	L M H ?	L M H ?	L M H ?
2-5	vegetation (dry, greening, green, drying)						
2-6	vegetation density (Low Medium Dense)	L M D	L M D	L M D	L M D	L M D	L M D
2-7	soil moisture (wet/dry)	W D	W D	W D	W D	W D	W D
3	**LOCUSTS**						
3-1	present or absent	P A	P A	P A	P A	P A	P A
3-2	area infested (ha)						
4	**HOPPERS**						
4-1	hopper stages (H123456F)	H 1 2 3 4 5 6 F	H 1 2 3 4 5 6 F	H 1 2 3 4 5 6 F	H 1 2 3 4 5 6 F	H 1 2 3 4 5 6 F	H 1 2 3 4 5 6 F
4-2	appearance (solitary, transiens, gregarious)	S T G	S T G	S T G	S T G	S T G	S T G
4-3	behaviour (isolated, scattered, groups)	I S G	I S G	I S G	I S G	I S G	I S G
4-4	hopper density (/site, /m2, Low Med High)						
5	**BANDS**						
5-1	band stage (H12345F)	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F
5-2	band density (/m2 or Low Medium High)						
5-3	band sizes (m2 or ha)						
5-4	number of bands						
6	**ADULTS**						
6-1	maturity (immature, mature)	I M	I M	I M	I M	I M	I M
6-2	appearance (solitary, transiens, gregarious)	S T G	S T G	S T G	S T G	S T G	S T G
6-3	behaviour (isolated, scattered, groups)	I S G	I S G	I S G	I S G	I S G	I S G
6-4	adult density (/transect, /ha, L M H)						
6-5	breeding (copulating, laying)	C L	C L	C L	C L	C L	C L
7	**SWARMS**						
7-1	maturity (immature, mature)	I M	I M	I M	I M	I M	I M
7-2	swarm density (/m2 or Low Medium High)						
7-3	swarm size (km2 or ha)						
7-4	number of swarms						
7-5	breeding (copulating, laying)	C L	C L	C L	C L	C L	C L

7-6	flying (direction, time passing)						
7-7	flying height (Low Medium High)	L M H	L M H	L M H	L M H	L M H	L M H
8	**CONTROL**						
8-1	pesticide name & formulation						
8-2	application rate (l/ha or kg/ha))						
8-3	quantity (l)						
8-4	area treated (ha)						
8-5	ground or air	G A	G A	G A	G A	G A	G A
8-6	estimated % kill						
9	**COMMENTS**						

kc 99.03

Was a GPS used to determine locations? yes no

Is a brief interpretation or analysis of the results included? yes no

Country: ______________________ Locust Office ______________________________ date : _________

cleared by : ______________________________ date : _________