Assessing the relationship between outbreaks of the African armyworm and climatic factors in the forest transition zone of Ghana

Ibrahim Adama

March, 2011

SUPERVISORS:
Dr. Ir. Anton Vrieling
Ms. Ir. L. van Leeuwen

Assessing the relationship between outbreaks of the African armyworm and climatic factors in the forest transition zone of Ghana

Ibrahim Adama

Enschede, The Netherlands, March, 2011

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Natural Resources Management

SUPERVISORS:

Dr. Ir. Anton Vrieling
Ms. Ir. L. van Leeuwen

THESIS ASSESSMENT BOARD:
Dr. K. de Bie (Chair)
Dr. A.J.W. de Wit (External Examiner) Alterra, Wageningen University

ABSTRACT

The African armyworm *Spodoptera exempta* (Walker) is a migratory moth, the larvae (caterpillars) of which are important pests, particularly in sub-Saharan Africa. This moth species also demonstrates great variability in the extent and severity of infestation. As such it is considered a serious outbreak pest of cereal crops and grasslands in Africa. The African armyworm is known to cause extensive damage to maize crops and rangeland in the transition zone of Ghana. This research is an investigation of the relationship between the Normalized Difference Vegetation Index, rainfall and temperature and how they influence the outbreak of this moth species in the Ejura-Skyedumase district of Ghana. The temporal patterns of the variables and their interrelationships have been evaluated through graphical, logistic and standardization z-score transformations. A strong similarity between temporal patterns of vegetation index and rainfall has been established. Likewise, the temporal pattern of temperature runs opposite to NDVI and rainfall patterns. Standardized NDVI anomaly has revealed periods of low vegetation index with corresponding high wetness denoting damage to vegetation due to the activities of the insects during outbreak. This revelation is a confirmation of reports gathered from local famers. NDVI therefore is a good predictor of armyworm outbreaks since a relationship was established between the occurrences of the moth species and multi-temporal 10-day NDVI signal. The much hypothesized assertion that rainfall and temperature influence the occurrence of armyworms has also been dealt with by assigning some climatic variability likely to influence the occurrence of the moth species.

Keywords: Armyworm, *Spodoptera exempta*, anomaly, outbreak, temporal pattern, relationship, NDVI, rainfall, temperature, multi-temporal, occurrence

ACKNOWLEDGEMENTS

First and foremost I would like to express my profound thanks to the Almighty Allah for his blessing, guidance, protection and abundance grace that strengthened me to deal with the multifarious challenges of academic and bachelor life.

Next I express much gratitude to the Netherland Fellowship Programme (NFP) for granting me this lifetime opportunity to broaden my social and academic horizon and pursuit of graduate studies in an international environment.

.

I wish to thank Dr. Ir. Anton Vrieling my first supervisor of the Department of Natural Resources Management ITC for his ceaseless patience, time and effort to supervise this work. I also thank Ms. Ir. L. van Leeuwen my second supervisor for her guidance and encouragement.

I am highly indebted to Professor Michael Weir for his fatherly advice and encouragement throughout my pursuit of the MSc. Program at ITC. I extend my gratitude to all the staff of the Department of ITC particularly Mr. Raymond Nijmeir for his immense assistance. The Director and staff of PPRS, Kumasi and Ejura Agric station of MoFA Ghana also deserve my commendation.

Many thanks to all the assistance and support from my friends and course mates of NRM class of 2010 for their friendship especially Ms Bana Mediatrice Rwamukwaya, Mr Satya Prakash Negi, Mr Hailemariam Gebrewahed Fanta and indeed all staff of ITC international Hotel for making my stay in Enschede a joyous and memorable one.

I also thank my wife Marie and children Hakeem, Mustapha and Jamaludeen for their love, patience and endurance for my absence from home during the period of study.

My acknowledgement would not be complete without the mention of my employers, Crops Research Institute, Ghana for granting me study leave for which I will forever be grateful.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ADAGUC	Atmospheric Data Access for the Geospatial User Community
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
AVHRR	Advanced Very High Resolution Radiometer
ENVI	Environment for Visualisation of Images
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
GSS	Ghana Statistical Service
IPCC	Intergovernmental Panel on Climate Change
IFPRI.	International Food Policy Research Institute
ITCZ	Inter-Tropical Convergence Zone
MODIS	Moderate Resolution Imaging Spectroradiometer
MoFA	Ministry of Food and Agriculture
NDVI	Normalized Difference Vegetation Index
NPV	Nucleopolyhedrovirus
PASW	Predictive Analytics Software
PPRS	Plant Protection and Regulatory Service
SPSS	Statistical Package for the Social Scientist
TRMM	Tropical Rainfall Measuring Mission

1. INTRODUCTION

1.1. Background

Insect outbreaks are caused by a dramatic change in the physical environment and variability in environmental conditions play an important role in triggering all types of outbreaks (Singh and Satyanarayana, 2009). Climate change as a result of increase in carbon dioxide and atmospheric temperature is expected to cause a negative impact on agriculture in various parts of the world (IFPRI, 2009). Besides impacts like drought or flooding, also agricultural insect pests will be affected. Changes in climatic conditions could profoundly affect insect population dynamics (Andrewartha and Birch, 1954; Green Bank, 1956; Woiwod, 1997) hence their damaging effect on crops. Consequently, agricultural production and food security in many African countries and regions are likely to be severely compromised (IPCC, 2007). Climate change will cause new patterns of pests and diseases to emerge, affecting plants, animals and humans (FAO, 2010).

The severity and frequency of insect pest outbreaks will depend on the variability and changes in environmental variables such as temperature and precipitation. This is because environmental factors play an important role in the physiological processes and distribution of insects. According to Ciancio and Mukerji (2007) plant pests are extremely dependent on climatic and environmental conditions since several phases of a pest's life cycle strictly depend on the combination of two or more environmental variables including rainfall, temperature and humidity. Global climate change, therefore, is likely to affect agro-ecosystems by frequent insect pest occurrence and increased rate of development of these animals (Fuhrer, 2003; Kiritani, 2006). Increasing insect outbreaks has been noted as "virtually certain" under such circumstances (IPCC, 2007).

The African armyworm *Spodoptera exempta* (Walker) is a migratory moth, the larvae (caterpillars) of which are important pests, particularly in sub-Saharan Africa, the Western Arabian Peninsula, Pacific Islands, south East Asia and Australia (Haggis, 1986). This moth species also demonstrates great variability in the extent and severity of infestation. It is a "serious outbreak pest of cereal crops and grasslands in eastern and southern Africa, devastating small-scale subsistence farms and commercial production alike" (Rose *et al.,* 2000). They occur in large numbers when there is an outbreak hence the name "armyworm". They travel in masses from one field to another in search of food to complete their development, devastating crops as they move. Significant yield losses are most consistently reported from eastern and southern Africa. However, in recent decades, the frequency of reports from West Africa has increased (Musobozi *et al.*, 2005). The African armyworm is known to cause extensive damage to maize crops and rangeland in the transition zone of Ghana. The area represents the transition from semi-deciduous forest to Guinea Savannah accounting for 28% of land area. The vegetation is mainly characterized by Agriculture, grassland and forest. Although there are periodic outbreaks across the country, the frequency of outbreaks in the transition zone is a major concern. The loss of large cropped areas affects agricultural productivity. Understanding why armyworm outbreaks occur is the first step towards the development of intervention strategies aimed at controlling the menace of these insect species.

Armyworm outbreaks can have catastrophic effects on farmer's crops, their livelihoods and food security. Estimated grain losses during outbreaks in individual locations have averaged 60 per cent but, in many cases there is total crop loss (Tanzubil and McCaffery, 1990). The most damaging outbreak occurred in Tanzania and Kenya in 2001 covering 157 000 hectares of crops and pasture affecting about 80 000 smallholder farms in 54 districts (Musobozi *et al*., 2005). The costs for controlling armyworm outbreaks in Ethiopia, Kenya and Tanzania closely approximated the value of saved crops (Rose *et al*., 1997).

The main armyworm control tool according to Mushobozi *et al.* (2005) is the application of chemical pesticides. Currently, increased efforts have been channelled into developing safe and environmentally friendly alternatives such as aqueous neem extract (Tanzubil and McCaffery, 1990). baculoviruses – nucleopolyhedrovirus (SpexNPV) (Grzywacz *et al*., 2008). Entomopathogenic fungi (Green Muscle) (Rose *et al*., 2000). Recently in Tanzania a monitoring and prediction system based on insect trap catches of moths in relation to rainfall has been practiced with some success (Mushobozi *et al*., 2005).

A reliable method of forecasting outbreaks will greatly enhance the application of control methods (Grzywacz *et al*., 2008). The common approach for analyzing the relationship between population dynamics and climatic variables according to Stenseth *et al.* (2002) is by means of simple correlation or using the climate as an additive covariable in statistical models. This will involve techniques such as remote sensing (RS), geographic information system (GIS) and ecological models which have the advantage of mapping the distribution of the insects and offer the most efficient and effective means to inform us about their spatial and temporal distribution (Philips *et al*, 2006; Webster and Oliver, 2007).

Monitoring of agro ecosystems through digital remote sensing techniques has greatly improved in recent years, and the technology now available seems suitable for routine use in many agro ecosystems management applications (Doraiswamy *et al*., 2005; Niemann and Visintini, 2005; Thenkabail *et al*., 2009). The launch of the Landsat sensors in the 1970s provided support for large scale insect damage mapping and monitoring (Kelly and Guo, 2007). Remote sensing is a promising technology that may provide early detection of localized infestations of these pests based on associated crop conditions (Allen *et al*., 1999). In particular, remote sensing provides observations useful for monitoring environmental conditions favourable to the reproductive success, development, dispersal, and survival of disease vectors, primarily arthropods and particularly insects (Snow *et al*., 1999). Early detection and accurate mapping of insect infestations can assist managers in optimizing within-field placement of agricultural practices (Pinter *et al*., 2003; Scotford and Miller, 2005) with numerous environmental benefits. Identification of infested areas can assist farmers to more accurately apply preventative measures such as pesticides application to pest density across a field (Weisz *et al*., 1995; Zhang *et al*., 2003).

It is important to note that field measurements are rarely available at a spatial scale that incorporates a range of spatial variability and sample variability and error present in field measurements limit their utility as 'ground truth' (Goetz *et al*., 2000). Researchers are therefore forced to use unrealistic assumptions of unreliable field measurements, which may lead to high uncertainties in modelling predictions of potential environmental impacts (Lunetta *et al*., 2010).

In view of the above, the normalized difference vegetation index (NDVI) derived by dividing the difference between infrared and red reflectance measurements by their sum which according to Kidwell (1990) provides a crude estimate of vegetation health and a means of monitoring changes in vegetation over time is appropriate. According to Hansen *et al.* (2003) and Shao *et al.* (2010) the phenology based categorization (or time-series analysis) of MODIS-NDVI is one of the most used approaches. NDVI according to Rahman *et al.* (2004) is an excellent and widely used method for crop growth and condition assessment. The use of spectral vegetation index, namely the Normalized Difference Vegetation Index

(NDVI) will be applied to detect areas of vegetation cover decrease which correspond to outbreak occurrence within the cropping season. Since it is virtually impossible to see an insect pest directly on a crop in remotely sensed imagery, it would be important to understand the relationship between the spatial variability of crop stress in the NDVI map and the spatial variability in the population density of the insect pest (Niemann and Visintini, 2005).

1.2. Problem statement

The economy of Ghana is agricultural dependent. Agriculture provides over 37.3% of the country's gross domestic product (GDP) (Schmitz, 2008). More than 60% of the population is engaged in the agricultural sector. The farming sector is dominated by small farms throughout the country. Over 70 % of the farmers cultivate on holdings less than three hectares (Chamberlin, 2007). About 80% of the farming population is resource poor who practice subsistence agriculture out of which 89% cultivate maize (GSS, 2004). Maize is Ghana's most important cereal crop (FAO, 2005). As the main staple especially for the people in the northern part of the country is also the primary feed ingredient for the booming poultry industry. It is grown by the vast majority of rural households in all parts of the country except for the Sudan Savannah zone of the far north. According to official statistics, the area planted to maize in Ghana currently averages about 650,000 ha per year. Grain yields of maize per unit land area are correspondingly modest, averaging less than 2 t/ha thus, about a third of the crop's yield potential (Schmitz, 2008). The situation is attributed to several factors such as diseases, weeds, water availability, soil fertility and insect pests.

Crop destruction by insect pest constitutes one of the most important constraints farmers face in their bid to produce food to feed the ever increasing population. The nation's aim to attain food self-sufficiency by 2020 would be illusive with regard to persistent infestations and destruction of maize fields by the African armyworm. The insects pose a serious threat to the agricultural sector and food security and therefore necessitate a quick response. Outbreaks and subsequent destruction of several hectares of maize fields occur predominantly in the Forest-Transition ecological zone also called the "maize belt" (Schmitz, 2008) of Ghana. In October 2006 and October 2009 nine districts and three farming communities in the Brong Ahafo region were seriously hit by armyworm outbreaks which devastated a total of 3,600 hectares of maize (Anon, 2009). In such situations, the livelihood of these resource poor farmers and their families as well as the food security status of the country is threatened.

1.3. Justification

The rapid development (short life cycle), high reproductive capacity and mobility by migration of the African armyworm influence its outbreak capacity (Mushobozi *et al.*, 2005). The dry spell between the major and minor rainy seasons (August - September) probably provides suitable environmental conditions for armyworm breeding in Ghana. According to Shank (1996), "climatic changes at the onset of the rainy season, particularly when following a drought season, result in production of abundant forage which may trigger some response in the females laying the eggs". The sudden and dramatic localized damage that can be inflicted by the African armyworm (Brown *et al.*, 1969) is however, the justification for trying to develop a predictive model to control the pests when they appear. Moreover, since young caterpillars are difficult to detect, there is hardly any time to react as infestations frequently occur unnoticed. From the fourth instar stage however, caterpillars become conspicuous and cause a lot of damage to crops in a very short time (Haggis, 1996). It is therefore important to investigate the suitable environmental factors that influence their occurrences. According to Holt *et al.* (2000) moths arriving at a new destination will lead to an outbreak or remain as a low density scattered population depending on the weather conditions at the destination. Models that predict the outbreak of armyworms have been developed in Kenya (Dewhurst *et al.*, 2001) and Tanzania (Holt *et al.*, 2000; Rose *et al.*, 1995). These were however, based on moth catches and precipitation. No such study has ever been carried out in Ghana. The Food and Agriculture Ministry in Ghana lacks the information for armyworm surveillance (Dr. J. Vespa Suglo Director PPRS of MOFA, Pers. Comm.). Preventive control of these pests before they become a serious problem is the major management technique. It is thus important to know the trend and scale of infestation. Environmental factors which influence insect behaviour can be monitored to deduce their relationship to insect outbreaks. The development of a decision tool to forecast armyworm outbreak as being high or low risk is based on rainfall patterns (Cheke and Tucker, 1995). Migration and breeding of the African armyworm therefore are stimulated by rainfall. (Holt *et al.*, 2000) stated that the timing and distribution of rainstorms is of fundamental importance in governing armyworm population processes. In this vein the patterns of rainfall could suggest clues to armyworm outbreaks since arrival and capture of moths in traps has been shown to be associated with rainfall (Dewhurst *et al.*, 2001; Tucker and Pedgley, 1983). Rainfall is also a major limiting factor in determining armyworm fecundity, as egg laying is assumed to increase from drier to wetter rainfall categories ((Page, 1988)) even though it is detrimental to very young larvae (Rose *et al.*, 1995). The duration of one armyworm generation (ca.5 weeks) is considered in relation to historical frequencies of rainfall to make a good forecast (Holt *et al.*, 2000). Temperature is generally known to affect the reproduction of several insect species. Mating and oviposition in the armyworm is strongly influenced by temperature. Beyond 25ºC mating and oviposition activity reduce considerably (Kanda and Oya, 1985). Air temperature is an involuntary factor which influences the determination of oviposition sites of the African armyworm (Rainey, 1976). A suitable temperature is essential for the viability and hatchability of eggs of this moth species (David and Ellaby, 1975).It sounds reasonable therefore to believe that temperature plays a vital role in population build up and consequently reaching outbreak levels.

NDVI based on remotely sensed advanced very high resolution radiometer (AVHRR) Images has been used as a proxy for canopy coverage and vegetation phenology to identify relationships between vegetation and meteorological variables over various spatial and temporal scales (Weiss *et al.*, 2003). The examination of a temporal sequence of satellite images allows changes in reflectance associated with disturbance to be quantified and has been found to be effective at characterizing disturbance events such as insect outbreaks (Kennedy *et al.*, 2007; Wulder *et al.*, 2005).

The outcome of this research therefore should fill the information gap and provide an early warning guide to inform farmers in particular and the Ministry of Food and Agriculture in general. The availability of such information will put the Ministry and farmers on alert for possible outbreaks.

1.4. Objective

The study therefore seeks:

1. To evaluate whether armyworm occurrence can be related to a multi-temporal 10-daily NDVI signal as derived from SPOT Vegetation
2. To establish a relationship between the occurrence of past outbreaks and climatic factors for the district.

1.5. Research questions

1. Can armyworm occurrence in the district be related to a multi-temporal 10-daily NDVI signal?
2. What kind of temporal relationship exists between outbreaks and climatic factors?

1.6. Hypothesis testing

Ho: Occurrences of the African armyworms in the district is not associated with the multi-temporal 10-daily NDVI signal.

H_1: There is a strong association of African armyworm occurrences with multi-temporal 10-daily NDVI signal.

Ho: There is no significant relationship between pest outbreak and climatic factors in the temporal domain

H_1: There is significant relationship between pest outbreak and climatic factors in the temporal domain

1.7. Thesis outline

This thesis contains seven chapters.

The first chapter contains the general overview of the research. The research problem has been clearly outlined and justified. Research objectives, research questions and hypothesis to be tested also stated. A brief outline of thesis structure is also presented.

The second chapter gives a vivid description of the study area and the reason that informed the choice of the study area. Chapter three looks at the biology, ecological characteristics of the insect under consideration, the African armyworm and its incidence on the maize crop.

Chapter four presents description of the datasets used in the study and the methodology employed for analysis. Results emanating from the analysis are presented in chapter 5.

Discussion of the results is presented in chapter 6.

Finally, conclusion and recommendation of key findings and future direction of the research are presented in the seventh chapter.

2. STUDY AREA

2.1. Site selection

The Ejura-Sekyedumase district was chosen for the study because of the dominance of maize cultivation in the country. The district, according to maize production statistics from the Ministry of Food and Agriculture is the highest in terms of maize production in Ghana. The Ministry of food and Agriculture records indicates that the district has experienced four armyworm outbreaks since 1989. Besides, majority of farmers in the district are maize producers. The effect of armyworm outbreaks in the district therefore threatens the livelihoods of several farmers and their families as well as food security in the country.

2.2. Ejura-Sekyedumase district

Ejura-Sekyedumase District with Ejura as Capital was established by a legislative instrument, PNDC L.I 1400, 1988. The district is located within longitudes 1˚5W and 1˚39' W and latitudes 7˚9' N and 7˚36'N. Its size is about 1,292.2km$^{2.}$ The landscape in the southern part of the district is slightly mountainous with a few depressions and high hills. The northern part on the other hand, is undulating and fairly flat with heights ranging between 150-300m. The district lies within the transitional zone of the semi-deciduous forest and Guinea Savannah zones. Thus, it experiences both the forest and savannah climatic conditions. The district is marked by two rainfall patterns; the bi-modal pattern in the south and the uni-modal in the north. The main rainy season is between April and November. The north-east trade winds blow dry and dusty winds across the entire district during this period. Annual rainfall varies between 1,200mm and 1,500mm.

Relative humidity is very high during the rainy season, recording 90% in its peak in June and 55% in February. Solar radiation is very high during the dry season. The vegetation characteristics in the district are to a large extent dictated by the topography, climatic condition and patterns. The northern part is covered with sparse derived deciduous forest vegetation. Growth of the savannah vegetation is largely attributable to the high increase in the rate of shifting cultivation and bush fallowing in the district. In addition, charcoal burning is a preoccupation of some migrants to the district. The climatic conditions of the district together with the topographical layout are a favourable condition for the cultivation of food crops. The soils are easy to till and especially suited for mechanized farming and therefore support the cultivation of food and cash crops. Root tubers such as yam and cocoyam as well as cereals such as maize do well especially in such soils. This explains why maize and yam are two of the major crops grown in the district. Maize is the dominant food crop type cultivated in the district since the soil type in the district supports the production of maize more than any other food crop. The district is also noted for the production of eggplant in large quantities. Cashew and mangoes are also popular fruit crops produced in the district. (http://www.ghanadistricts.com/districts/?r=2&_=22&sa=5681)

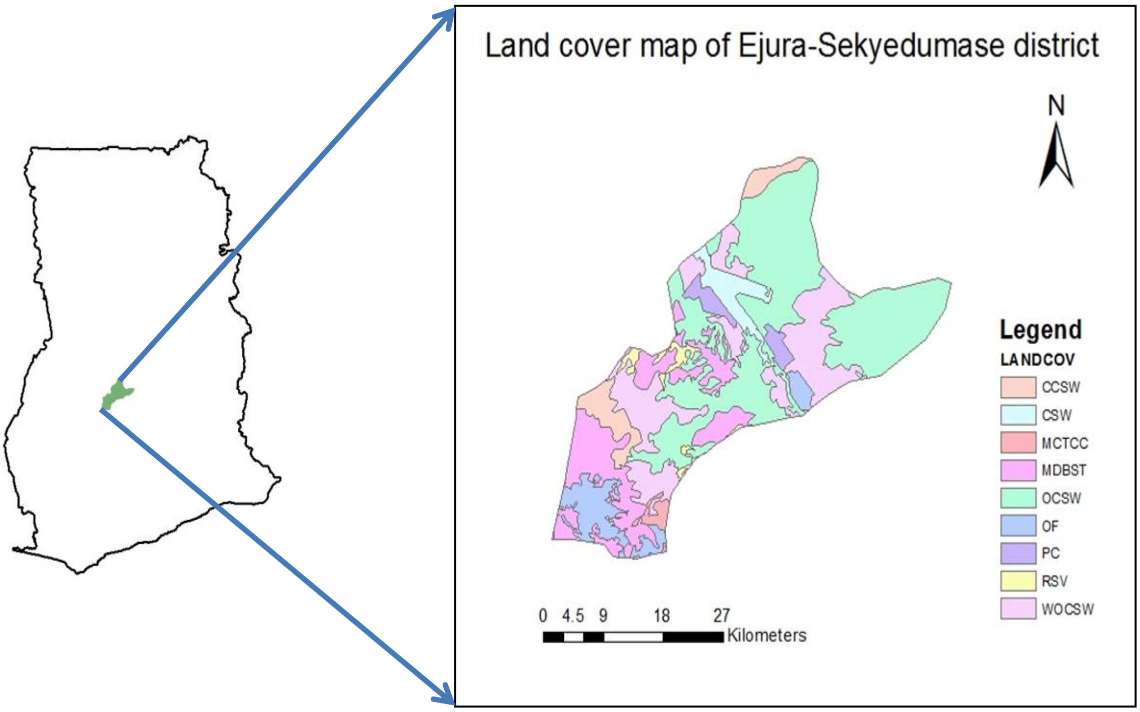

Figure 2:1 Outline of Ghana map showing the study area

2.3. Transitional zone

Ghana is divided into six agro-ecological zones reflecting the climatic, vegetation and soils distribution (Table 2.1).The transitional zone located in the middle belt of Ghana is found mainly in the Brong-Ahafo and Ashanti regions. The area also covers the northern part of the Volta region and the southern part of the Northern Region. The area represents the transition from semi-deciduous forest to Guinea Savannah. The vegetation is mainly characterized by agriculture, grass land and forest. The transitional zone covers a total area of 8,400 km^2 and 28% of the total area of Ghana (FAO, 2005). It is the most suitable area for agriculture and has the highest production of maize in Ghana (FAO, 2005; Schmitz, 2008). The soils are fertile and the climate with annual rainfall of 1000 – 1300 mm fits very well with crops like maize, cassava, yam, eggplant and pepper (Dickson and Benneh, 1988). The southern part of the area has a bimodal rainfall pattern (major: March-July; minor: September- November) allowing for two harvests per year. .The northern part on the other hand experiences uni-modal pattern of rainfall and resultantly enjoys only one harvest a year. Although there are reports of occasional armyworm outbreaks across the country, there appears to be a cyclic trend of outbreaks in the transitional zone. This therefore calls for investigation for a long term solution of the problem.

Table 2-1 Characteristics of agro-ecological zones of Ghana

Zone	Rainfall	Portion of total area	Length of growing season	Dominant land use systems	Main food crops
	(mm/yr.)	(%)	(days)		
Rain forest	2 200	3	Major season: 150-160 Minor season: 100	forest, plantations	roots, plantain
Deciduous forest	1 500	3	Major season: 150-160 Minor season: 90	forest, plantations	roots, plantain
Transition Zone	1 300	28	180-200	annual food and cash crops	maize, roots plantain
Guinea savannah maize	1 100	63		annual food, cash crops livestock	sorghum,
Sudan sorghum Savannah	1 100	1	150-160	annual food crops livestock	millet, cowpea
Coastal Savannah	800	2	Major season: 100-110 Minor season: 50	annual food crops	roots, maize

Source: http://www.fao.org/fileadmin/user_upload/aquastat/pdf_files/GHA_tables.pdf

3. BIOLOGY, ECOLOGY AND INCIDENCE OF THE AFRICAN ARMYWORM

3.1. Biology of the African armyworm

The African armyworm *Spodoptera exempta* (Walker), is among the most devastating crop pests in Africa, with the larval stage of the moth being a major defoliator of exclusively staple cereal crops as well as pasture grasses belonging to the Gramineae family. It occurs widely in the grasslands of tropical and subtropical areas of Africa, the Western Arabian Peninsula, Pacific Islands, south East Asia and Australia (Haggis, 1986). In Africa, *S. exempta* occurrence is confined to countries south of the Sahara. It is of major economic importance in countries of East and South Africa. In recent decades however, there has been increasing reports of its occurrence in West Africa especially Ghana. According to Kabissa (2008), "in typical armyworm outbreaks, larval density may exceed 1,000 per square meter over areas covering tens or even hundreds of square kilometres".

The adult is a medium sized moth, measuring 2.0 to 3.7 cm in wingspan. It is very active at night. The forewings show a dull grey-brown appearance. The hind wings are whitish with dark veins. The sexes can be differentiated by the presence of bristles on the frenulum which are single in the males and multiple in the females. A characteristic distinguishing feature of the African armyworm is the presence of racquet-shaped scales at the tip of the abdomen of the males while the females have black scales at tip of the body. Females of *S. exempta* lay a total of 1200 eggs in clusters between 100 to 400 eggs per night covered by black scales from the tip of their abdomen. Eggs are small, 0.5 mm in diameter mostly laid on the underside of leaves and they are pale yellow in colour when newly laid, but darken until just before hatching. This takes about 2 to 4 days after oviposition. There are six larval instars extending over a period of between 14 to 22 days depending on the temperature and the host plant on which the larvae feed. Fully grown sixth instar larvae are usually 25 to 35 mm long. Pupation occurs 2 to 3 cm below the soil surface. Adults emerge within 7 to 12 days after pupation and can live up to 14 days depending on the food source.

3.2. Climatic characteristics influencing armyworm development and outbreaks

The development, distribution and infestation of the African armyworm like all insects can substantially be influenced by climate. Bryceson and Cannon (1990) did emphasize that in addition to precipitation and vegetation, other environmental variables such as temperature and sunshine are important in determining habitat suitability for the population development of insects. The adult moths upon emergence have the tendency to move to new areas and depending on the wind direction determines the extent of travel. They are mostly carried in a downwind direction during the night. According to Kabissa (2008), the moths first move up onto the trees and they fly up several hundreds of meters into the air, where if caught up by prevailing wind, are carried away downwind. The journey continues with intermittent stop overs during daybreak until they reach a suitable site usually where rain is falling. As Holt *et al.* (2000) puts it, movement and initiation of *S. exempta* colonies is stimulated by rainfall. The relationship between wind, rainfall and armyworm outbreaks has been expressed by several authors, including (Dewhurst *et al.*, 2001; Kabissa, 2008; Odiyo, 1979; Rose *et al.*, 1997) It is believed that prevailing winds as a result of the rainstorm facilitate their concentration at the site to initiate a colony. According to Holt *et al.* (2000) Rainfall determines emigration from the source outbreak, and aggregation, fecundity, mortality and food quality at the potential destinations of the displaced moths. If the new site is found suitable this depends largely on the climate (Holt *et al.*, 2000) they mate and lay eggs. Analysis of multi-temporal rainfall trends is likely to give a relation to outbreaks. Female moths require access to water to achieve hydration and maturation of their oocytes if they are to achieve their potential fecundity (Gunn and Gatehouse, 1985) Oviposition has been observed to occur during subsequent evenings. Since mating, oviposition and hatchability of eggs are influenced by temperature, the temperature at the beginning of the growing (outbreak season) is worth exploring for clues of relationship to occurrences. The female moths then disperse singly on grass stems where they laid their eggs. By the time the eggs hatch usually in 3-4 days, there was a flush of new grasses upon which the caterpillars feed (Rose *et al.*, 1995).

In view of the importance contribution of climate in the development and outbreak status of this moth species, changes in climate therefore would result in changes in population growth rates, increases in the number of generations and extension of the development season. Additionally, there would be changes in crop-pest relations, changes in interspecific interactions and increased risk of invasion by migrant pests as well as the initiation of outbreaks and changes in geographical distribution (Drake, 1994; Peacock *et al.*, 2006). Seasonal variation in climate therefore controls the outbreak of the African armyworm in various tropical regions. Two early theories were presented to account for the possible causes of outbreak of the African armyworm. According to Faure (1943), the adult moth migrated from unknown areas where the insect were able to breed throughout the year to outbreak destinations. Hattingh (1941) on the hand had earlier on argued that the buildup of *S. exempta* populations occur rapidly out of a low density one. Migration therefore according to (Elewa, 2005) is a mechanism by which organisms avoid unfavorable environments for more conducive ones. Evidence for mass migration by *gregaria-phase* moth populations is now beyond dispute particularly upon emergence from outbreak locations (Rose *et al.*, 1995).

3.3. Ecological characteristics of the African armyworm

The caterpillars of this moth species adapts well to its environment by exhibiting a density dependent phenomenon called phase polyphenism. A situation in which, two or more phenotypes occur in a population as a result of exposure to different environmental conditions. The insects are capable of transforming from one 'phase' to another and according to Cheke (1995) such a situation occur as a result of both physiological and behavioural changes. Amongst these changes are temperature, food and population density as evidenced from laboratory and the field studies. He added that in the gregarious phase the insects took shorter time to complete their life cycle. In this case the more aggressive aggregated type often referred to as gregarious phase and a scattered less active population known as solitary phase are exhibited. Before the third moult, all larvae remain green in body colour. However, depending on larvae population at this stage they will turn black or remain in various shades of green or brown. In a situation where there are large numbers of larvae present as in a typical outbreak situation, larvae tend to be characteristically velvety black on top with pale lines on each side and greenish-yellow underside; this phenotype is called the gregarious phase. It is during this phase that the insect is most devastating to crops. Larvae in the gregarious phase tend to be very active especially during the night and often march on the soil in one direction only looking for fresh food destroying host plants that come their way. They also feed high on plants during the day. In a less dense population, however, the developing larvae remain one of the many shades of green or brown colour until they pupate. Contrary to the gregarious larvae, they are sluggish, living mostly singly at the bases of plants and are not as destructive to crops as the former. Even though there are differences in their appearance, they remain the same insect species and one may easily be converted into the other. It is believed that the solitary form is the one that enables the populations to persist at a low level during the dry season when there are no outbreaks occurring.

Outbreaks follow the onset of wet seasons when dry grasslands produce new growth and cereal crops are planted. According to Janssen (1993) a marked seasonal occurrence of outbreaks arise soon after the start of the short rains (October-November) in East Africa Prolonged drought conditions usually preceded major armyworm outbreaks (Haggis, 1996; Harvey and Mallya, 1995; Tucker and Pedgley, 1983). This situation coincides with the dry spell which usually precedes the onset of the minor season in Ghana. Seasonal rains are influenced by the meeting of large scale winds from the northeast and the southwest at the Inter-Tropical Convergence Zone (ITCZ) in Africa. In East Africa, initial outbreaks are termed primary outbreaks which usually occur in November and December. Moths that emanate from such outbreaks are carried by the wind towards the ITCZ area where the rains are just beginning, and so they breed and multiply yet again. If conditions are suitable, they will increase at a faster rate within a short time. In Ghana, it is believed that they remain in the solitary phase during the off season until such time that conditions are favourable often the short dry spell preceding the second rainfall season is suspected to be aggregation, mating and egg laying period leading to population build up and consequent outbreaks. In East Africa however, it has been established that armyworm disappear during the dry season and survive in the solitary state along the coastal and highland areas which experience rainfall throughout the year (Dewhurst *et al.*, 2001; Haggis, 1996; Holt *et al.*, 2000; Rose *et al.*, 1997). Kabissa (2008) stated that there are seldom armyworm outbreaks in any part of eastern Africa from September to November. This is in contrast to the situation in Ghana where outbreaks mostly occur between September and November. Apart from the intervention by farmers and agricultural managers to protect crops from destruction by these insects, birds and insect natural enemies' aid in armyworm control, but may not exert enough pressure to prevent yield loss. Studies in East Africa have indicated that all life stages of the armyworm are subject to attack by a variety of natural enemies. For example, caterpillars are infected by an endemic baculoviruses - nucleopolyhedrovirus (SpexNPV), but armyworm deaths due to this virus occur too late in the armyworm season to stop the caterpillars from causing damage (Grzywacz *et al.*, 2008). Also, Entomopathogenic fungi (Green Muscle) (Rose *et al.*, 2000) and *Normuraea rileyi* have been found to attack the caterpillars during high humidity and temperature conditions (Kabissa, 2008). The larvae and adults also suffer parasitism from several arthropod species in the Diptera, Hymenoptera and Coleoptera orders.

3.4. Incidence of the African armyworm on the maize crop

During armyworm outbreaks, feeding damage by *S. exempta* to cultivated and wild host plant species is almost entirely restricted to the leaves. The larvae of this moth feed almost exclusively on plants of the families Gramineae. The crop mostly affected under the circumstance is maize. The young larvae initially eat the upper and lower parts of the leaf by scraping the surface tissues. With time the larvae feed gregariously and skeletonize the foliage thus leaving only the mid rib of the leaves on the stalk. As a rule, armyworm larvae tend to prefer young plants and newly germinated crops, often defoliating them to ground level during heavy outbreaks. This probably explains why they strike usually during the seedling stage of the maize crop. It is estimated that two larvae can completely destroy a 10-day-old maize plant with 6 to 7 leaves and a single larva can consume 200 mg of dry mass of maize leaves in the course of the sixth instar period (Kabissa, 2008). Destruction of maize during major outbreaks often necessitates replanting of the entire affected crop. In Ghana, cases of replanting have been mostly unsuccessful because the minor planting season is short and most importantly agriculture is primarily rainfall dependent. As such, armyworm outbreaks at the local level result in total crop loss within a short time. In other words, crop losses due to sudden outbreaks can be potentially devastating to local farmers and national economies since they occur mostly in Africa's impoverished countries.

The sporadic nature of outbreaks and the lack of efficiency for total control by natural enemies call for the exploration for effective control measures. Much as efforts are geared towards looking for efficient intervention strategy, the potential of the natural control organisms could as well be exploited.

4. MATERIALS AND METHODS

4.1. Data used

4.1.1. Armyworm outbreak data

The field work was carried out between September 16th and October 14th 2009 in the Ejura-Sekyedumase district within the transitional zone of Ghana. The stratified random sampling scheme was employed. The district was stratified into outbreak and no outbreak locations. Stratification was based on armyworm outbreak data showing communities and years of attack provided by the Plant Protection and Regulatory Service (PPRS) of the Ministry of Food and Agriculture. In each stratum, 10 each of outbreak and no outbreak communities were randomly selected. Field data consisted of crop calendar information and geographical locations farms under maize cultivation during past outbreaks were obtained by conducting farmer interview. The interview was based on their cropping history and whether or not they have ever experienced armyworm outbreaks and the method of control employed at that circumstance. With the use of a global positioning system (GPS), precise geographical locations of fields purported to have suffered outbreaks were recorded. Choice of outbreak locations was however based on farmers' response. A structured questionnaire (Appendix 1) was used for the interview. In all, seventy farmers were interviewed and geolocations of farms which either experienced outbreaks or not also taken.

4.1.2. Rainfall data

Dataset comprising rainfall and average temperature were used in this study. Daily rainfall records for the period 2005-2009 covering the study area was accessed from the Tropical Rainfall Measuring Mission (TRMM) web data resources. It consisted of precipitation TS (time-series) datasets which are daily variation in precipitation on low spatial resolution grids (0.25 x 0.25 degree resolution). The data was extracted in ASCII format for three individual pixels covering the study area and transferred into excel. (http://disc2.nascom.nasa.gov/Giovanni/tovas/). The 10-day accumulated rainfall data was derived by summing the values for day 1 to day 10, 11 to 20 and 21 to 31 for each month. This was done in order to put the daily rainfall data into similar format like the NDVI 10-day product for fair comparison. Additionally, the establishment of a relationship between rainfall and insect behaviour and for that matter outbreak (Bryceson and Cannon, 1990; Holt *et al.*, 2000; Kabissa, 2008; Odiyo, 1979; Rose *et al.*, 1997), it would be ideal to explore temporal patterns of this variable for clues.

4.1.3. Temperature data

The temperature data also in daily recorded format was downloaded from ADAGUC surface temperature web portal. http://geoservices.knmi.nl/adaguc_portal/index.html. This dataset provides daily temporal global land surface temperature with a spatial resolution of 0.25 degree. The data was extracted similarly as described above and averaged into 10-day products for consistency. In other words, ten daily temperature values were averaged into one 10-day value. The gridded datasets allow for comparison of temporal variation in climate with the occurrence of outbreaks in the different years (Mitchell and Jones, 2005).

Rainfall and temperature offer immense contribution to the ecological characteristics of *Spodoptera exempta* and therefore exploring their effects are likely to enhance the establishment of relationship to outbreak. The organization of these factors into decadal products will enhance easy comparisons with time of occurrence. The choice of the climatic factors was based on the assertion that they influence ecological behaviour and development of this moth species (Guppy, 1961; Pond, 1960; Simmons, 1992)

4.1.4. NDVI vegetation time series data

The NDVI data used consisted of geo-referenced and cloud free SPOT-5 vegetation 10-day composite NDVI images at a resolution of 1km² from April 1998 to October 2010 obtained from http://www.vgt.vito.be/ The NDVI data are derived from the red and near-infrared bands as follows: NDVI = (near infrared - red)/(near infrared + red) (Tucker, 1979). NDVI composition involved pixel-by-pixel processing to determine the maximum value during each 10-day period. An iterative Savitzky-Golay filter was applied as in Chen *et al.* (2004). Further processing including subsetting and made available by Dr. Anton Vrieling ITC. For the purpose of this study a subset of the data covering 2005 – 2009 (180 decadal images) for which the African armyworm outbreaks have occurred in the district was extracted. The NDVI time series were extracted per pixel based on the field data locations.. Three 10-day composite available for each month were averaged to account for the mean monthly NDVI particularly for the outbreak month as well as inter annual comparison (Tan, 2007). The NDVI dataset provided temporal coverage for every ten days and was used to measure temporal variability of vegetation disturbance within the five year period on the premise that healthy vegetation cover are areas with high NDVI values, while disturbed vegetated or unhealthy areas have lower values.

4.1.5. Landsat image

A Landsat 7 ETM+ image of February 2007 covering the study area was acquired from the remote sensing laboratory of ITC.

4.2. Methods

4.2.1. Spatial pattern of outbreaks

Using Erdas Imagine Classic 10.0, the attributes of the Landsat image was processed to cover the study area by masking the attributes to the district outline. Geographical locations of field data collected were overlaid to show the spatial extent of outbreak coverage of the study area. This was further processed into a false composite (RGB: 452) of the image which reflects the vegetation characteristics of the district with reference to outbreak and no outbreak of the worms of the study area.. Overlaying field locations on presence/absence of armyworm outbreak could help to identify whether land use pattern may affect armyworm occurrence in the area. This analysis was carried out purely on the basis of visual interpretation.

4.2.2. NDVI data analysis procedure to monitor vegetation conditions and its variation with time

Geographical locations of field data collected were overlaid onto the NDVI vegetation time series image. Temporal profiles were then extracted for the pixels covering locations where field data were collected (Gutman, 1987). Using the available NDVI profiles, Analysis focused on the 10-day, monthly and annual periods over 2005 to 2009 time period. NDVI profiles were studied visually by exploring the pattern over time. In comparison to crop calendar information, it showed good temporal representation of vegetation disturbance. This was detected by associating low NDVI values in mean stacked NDVI images of 10-day composite. The resultant NDVI graphical output exhibited some variability suggesting a relationship to the damage by the African armyworm. Using the Predictive Analytics Software (PASW 18) (Cronk, 2010), the current version of the Scientific Package for the Social Scientist (SPSS) Differences emanating were considered statistical significant when $\boldsymbol{P}<0.05$.

Statistical analyses were performed to confirm the relationship observed during the graphical visualization. In view of the binary nature of the dependent variable being outbreak and no outbreak, logistic regression best fit for the analysis for the elucidation of the effect of the predictor environmental variables. According to Agresti (2002) Logistic regression can be used only with two types of target variables: A categorical target variable that has exactly two categories (i.e., a *binary* or *dichotomous* variable), that is, the dependent variable can take the value 1 with a probability of success or the value 0 with probability of failure and the independents are of any type. A stepwise regression technique, which automatically selects the most statistically significant predictors among the input potential predictors, was used to establish a relationship to answer research question 1, whether indeed the activities of the insects would be reflected in the 10-day NDVI temporal data. Wen and Zhang (2010) used a stepwise regression and time series data to study fluctuations of *S. exigua* outbreak frequency. The field locations on presence/absence of armyworm outbreak were regressed with the 10-day NDVI for August, September and October 2006 2009.

4.2.3. Meteorological data analysis procedure

Rainfall and temperature time series were extracted for each of the three pixels covering the study area. Time series plots of both climatic variables were used to identify whether clearly different climatic conditions occurred during outbreak years as compared to non-outbreak years. The assessments were based on visual interpretation of 10-day, monthly and yearly profiles variation and trends. As the climate data only covered three pixels, regression analyses that investigate spatial relations between climate and outbreak occurrence could not be performed.

4.2.4. Profile analysis and interpretation

To ascertain a clear relationship between NDVI and climatic factors, the generated profiles were again compared by graphical visualization for possible clues to determine a response by the insects. According to Blackburn (1996) profile analysis is proving to be a useful tool in interpreting the pattern of tests or scores and may be across groups or across scores of individual variable. In addition, to observe differences in the patterns, relationships were explored between anomalies in the vegetation indices and the climatic information. The NDVI standardized anomalies which is the departure of NDVI from the long-period average, normalized by the long-period variability was employed. It indicates whether the vegetation greenness at a particular location is typical for a particular averaging period of the year. Ten-day anomalies are generated from the 10-day NDVI and climatic datasets. The transformation used in this study was the 10-day Z-score, which involved taking the set of values for a given month for example all Januarys and computing their Z-score value. This is achieved by subtracting the mean and dividing by the long-period standard deviation for that decade of the year, for each grid cell. The reference period is 2005 to 2009. The standardized seasonal anomalies were calculated with the use of z-score transformation:

$$z_{tj} = \frac{x_{tj} - \overline{x_j}}{s_j} \quad (1)$$

where $\overline{x}$j and sj denote the long-term means and standard deviations, respectively, for month j, and t is a time index (Steinbach *et al.*, 2002; Udelhoven *et al.*, 2009). To test the correlation between precipitation and NDVI, graphical comparison of the temporal sequences of NDVI and rainfall was used as an explorative test of a relationship (Debien *et al.*, 2010). To further explore relationships between armyworm outbreaks and variation in climatic factors descriptive statistics and visual comparisons were employed to determine relationship.

4.3. Software used

Among the software used during the study included ArcGIS 10.0 for data preparation, analysis and composition of maps. Erdas Imagine Classic 10.0 was used for image processing, extraction of NDVI and temperature data. ENVI 4.7 was used for profile analysis, PASW 18 for statistical analysis and Microsoft Office 2010 (Word and Excel) for graphics and reporting.

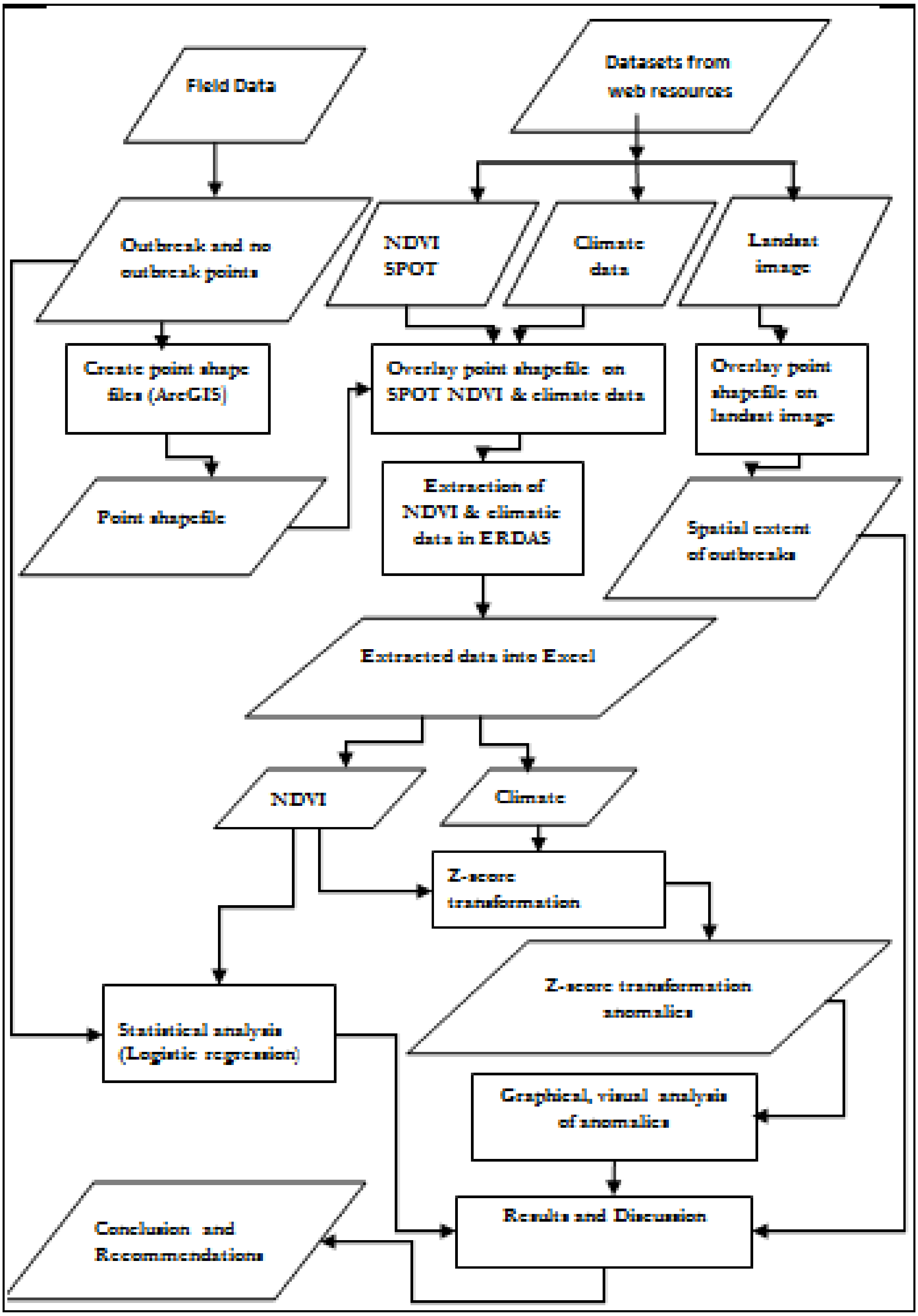

Figure 4:1 Summary methodological flowchart of the research

5. RESULTS AND DISCUSSION

5.1. Spatial pattern and potential factors to explain differences in outbreaks

The spatial distribution of armyworm outbreaks follow ecological gradient as per figure 5.1 below. The general pattern of outbreak is evident in the eastern part of the district characterized by savannah type vegetation with predominantly grassland and maize cultivation. The western portion on the other hand has more forest cover and varied cropping patterns recorded mostly no outbreak. The difference of vegetation patterns within the district is a possible reason to inform the differences in outbreak levels.

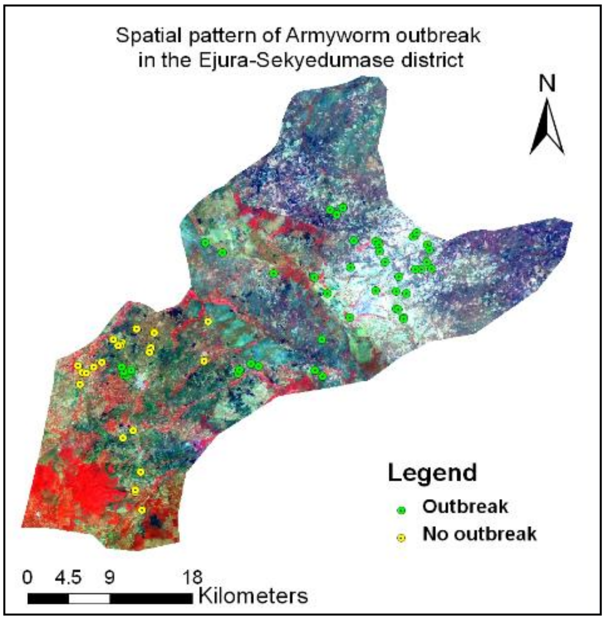

Figure 5:1 spatial distribution of outbreak and no outbreak of armyworm on a false composite map of the district

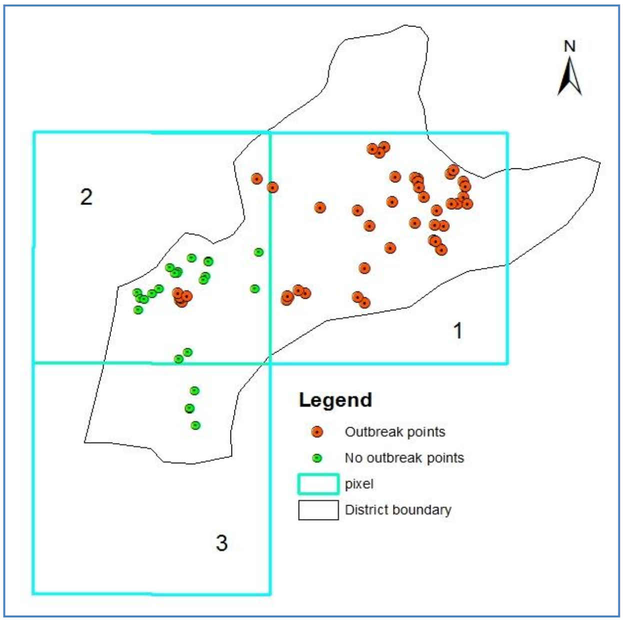

Figure 5:2 Grid cell for climatic data extraction

Spatially, more outbreak locations occurred in the north-eastern portion of the district whereas no outbreak areas mostly found in the south-western part of the district. A few outbreak points however occurred within the no outbreak area. The spatial distribution of armyworm outbreak in the Ejura-Sekyedumase district shows that 67 % of the locations are situated in the north-eastern part of the district which belongs to the savannah ecological zone and is dominated by grasslands and mono-culture maize cultivation. Dalin *et al.* (2009) confirm that insect pest outbreak risk is higher in monocultures and that monocultures may provide favorable conditions for population growth. Large populations of insect pests, especially polyphagous species migrate en masse to newly establish vulnerable crop monocultures (Altieri *et al.*, 1984). The south-western part of the district with some forested vegetation and varied cropping pattern recorded mostly no outbreaks. This could probably be due to the seemingly aggregated vegetation serving as wind break. Wind flow is impeded and affects moth transport to the area. Equally, ecosystems of varied vegetation balance enhance the activities of herbivorous natural enemies (Dalin *et al.*, 2009) The few outbreak locations within the area could probably be as a result of opening the area to extensive maize cultivation since transforming natural habitats into monocultures also leads to reduced biodiversity and increased risk of insect outbreaks (Roschewitz *et al.*, 2005).

Figure 5.2 shows the pixels for which the values for rainfall and temperature were extracted. Pixel 1 contains only field locations with outbreaks; pixel 3 also contains no outbreak field locations whereas pixel 2 has both outbreak and no outbreak field locations.

5.2. Monitoring of vegetation conditions with variation in time

5.2.1. Temporal patterns of vegetation condition

Figure 5.3 illustrate a comparison of 10-day NDVI and rainfall amounts during the observation period for pixel 1 in the outbreak area. Monitoring vegetation conditions with variation in time was based on the analysis of decadal NDVI imagery. As reported by majority of farmers in the district that they experienced armyworm outbreaks in October of 2006 and 2009, the graphical representation show clear negative NDVI anomalies for October 2006 (arrowed) with a corresponding positive wetness within the period. The high rainfall recorded during the period rules out the possibility of drought and therefore suggests there was vegetation disturbance during that time. It will be too early to say however that the poor vegetation condition was due to damage caused by this moth species. The situation in 2009 is completely different from observation by the farmers. A positive NDVI is shown with a matching negative precipitation. The NDVI for October 2009 even though positive was very low. The low vegetation index gives some signal to vegetation disturbance which is difficult to explain form this study. Nonetheless, in 2006 however a period of dryness is observed with high vegetation cover i.e. July-August which probably could have been a dry period with moderate precipitation likely to create a congenial atmosphere for moth concentration, purported by several studies (Haggis, 1996; Harvey and Mallya, 1995; Janssen, 1993) to attract the insects to breed. Contrary to my expectation no such signal can be observed in 2009.

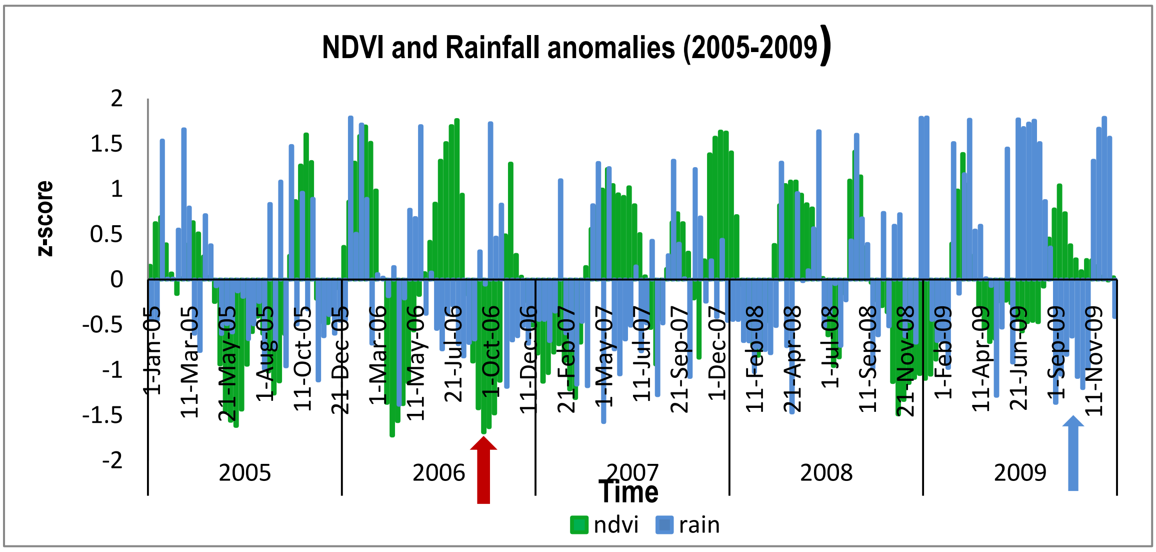

Figure 5:3 Time series analysis of standardized NDVI and rainfall anomalies of a selected location for Ejura-Sekyedumase district. Red arrow shows negative NDVI anomaly (Oct, 2006) and blue positive NDVI (Oct, 2009)

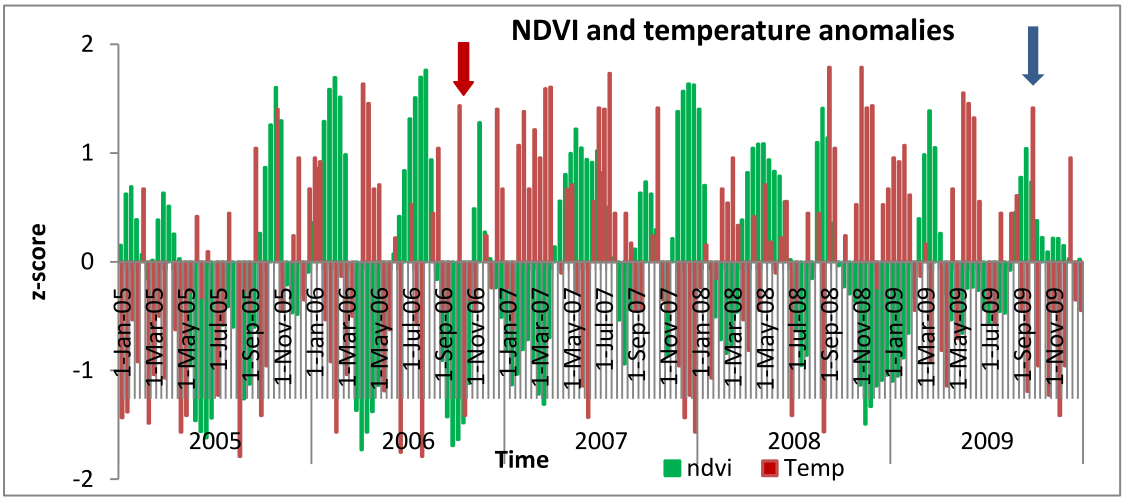

Figure 5:4 NDVI and temperature anomalies. Red arrow shows negative NDVI, high temp and blue arrow positive NDVI high temp.

Unlike rainfall, temperature anomaly (fig. 5.4) saw a sharp drop in October 2006 during which a negative NDVI anomaly was registered. A similar trend occurred in 2009 for temperature even though a positive NDVI anomaly was observed. It is evident that during the period of high wetness amidst very low NDVI, high temperatures were observed but drop suddenly.

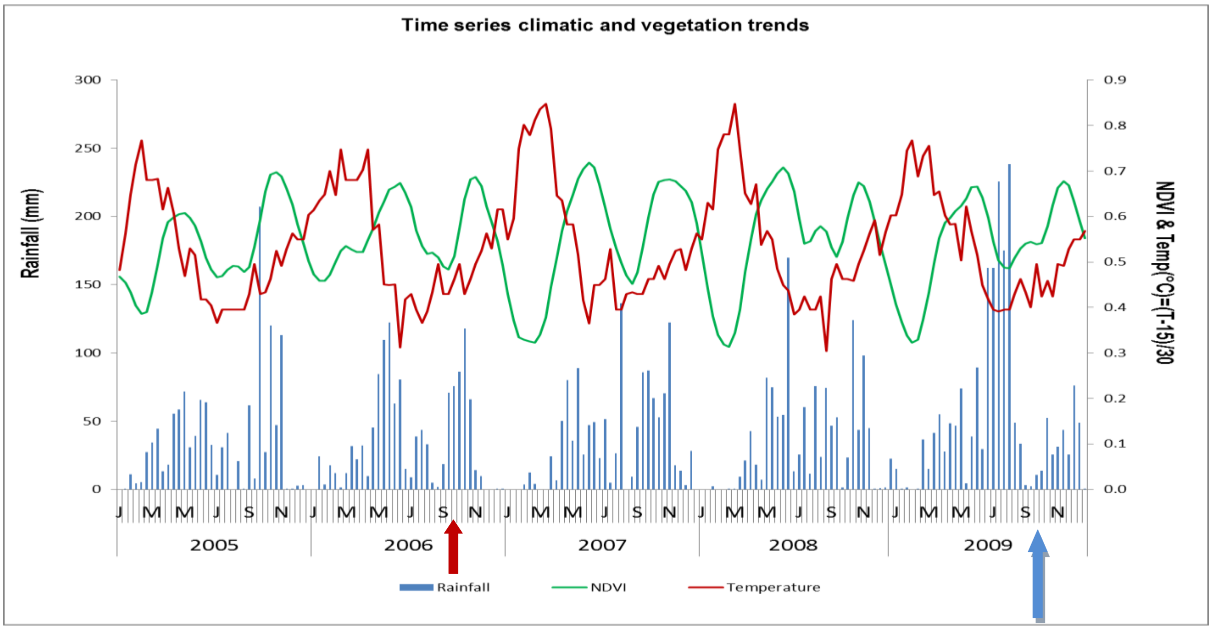

Figure 5:5 Annual variation patterns of average vegetation, rainfall and temperature within the period (2005-2009) Red arrow shows October 2006 while the blue arrow points to October 2009

5.2.2. Temporal patterns denoting outbreak

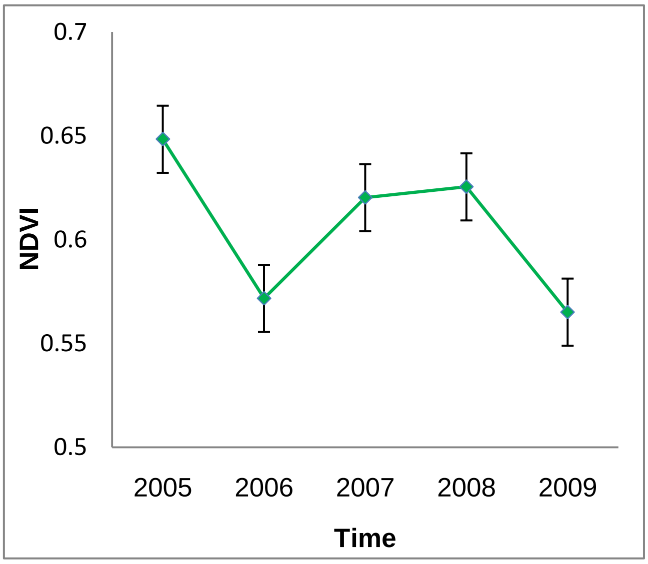

Figure 5:6 Average monthly (October) NDVI performance of fields during outbreak with

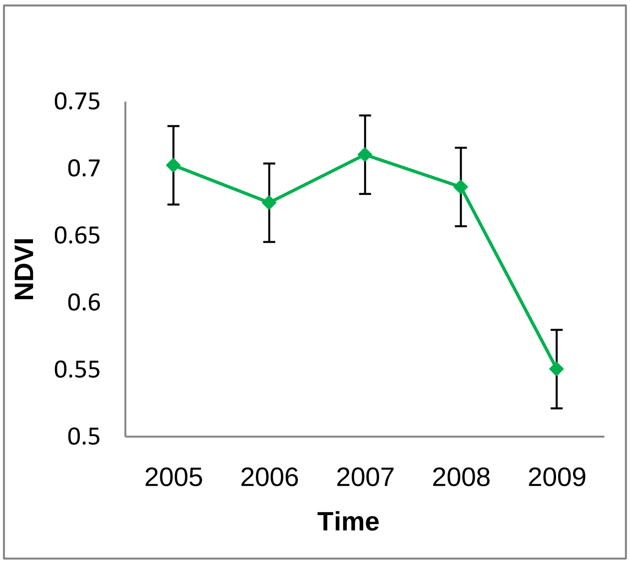

Figure 5:5 Average monthly (October) NDVI performance of fields which never experienced outbreak with time.

The positive NDVI anomaly in October 2006 was quite low which suggest some vegetation disturbances but difficult to explain at this point.

Generally, rainfall and NDVI followed a similar pattern whereas temperature on the other hand showed a contrasting one. As can be observed in figure 5:5 temporal variation of NDVI is directly influenced by precipitation. In other words, high NDVI correspond with high precipitation and vice versa. This result corroborates with that of (Anyamba *et al.*, 2002; Davenport and Nicholson, 1993; Tucker and Pedgley, 1983; Wang *et al.*, 2003) who established that rainfall is positively associated with NDVI.

Temporal analysis of monthly mean NDVI across the period of consideration showed an interesting pattern. A sudden dip in greenness for 2006 picking up gradually in 2007 and 2008 but dipped again in 2009 (fig. 5.6). This observation occurred in areas claimed to have suffered outbreaks in 2006 and 2009 by farmers interviewed. The temporal NDVI analysis revealed low vegetation indices in October 2006 and 2009 and the result confirm reports by farmers on the period of outbreaks. The time series mean monthly NDVI plots for a selected outbreak site illustrate that the October 2006 time periods showed the most pronounced anomalous vegetation greenness associated with the minor cropping seasons between 2005 and 2009. Statistically, the dip for 2006 outbreak locations was significant ($p<0.05$) as compared to no outbreak locations. A look at areas where there was no report of outbreak also showed a similar trend (fig.5.7) but the reduction in greenness in 2009 is not significantly different from the outbreak locations in that year. This is difficult to explain because level of wetness at the time was fairly good. Possibly, something might have happened for which its explanation is beyond the scope of this study.

The temporal pattern of rainfall contrasted with temperature as depicted in the figure 5. 9. In other words high rainfall amounts corresponded with low temperatures. This trend of affairs however is considered normal as it agrees with results of several other studies including (Rebetez, 1996; Reperant *et al.*, 2010). It is important to note that climatic variability is referred to variations in the mean states of weather in each temporal scale (Cardenas *et al.*, 2006) In 2006, there was rainfall and temperature variability particularly in the month of August in which the amount of rainfall recorded was quite moderate accumulated rainfall of 45mm with fairly low temperatures and moderate NDVI probably suitable for moth aggregation and subsequent breeding. According to Hill and Atkins (1983), concentration of adult moths resulting from climatic factors is judged to be the most likely mechanism for outbreaks. As shown in figure 5.8 such moderate accumulated amounts of precipitation and corresponding NDVI and temperature could be a contributing factor for that year's outbreak. In contrast to 2009 the month of August witnessed heavy precipitation. The pattern of rainfall with regard to the onset of the minor season was varied. The pattern seems different for all years. Temperature has been fairly consistent at the beginning of the minor growing season for the five year period. The probability of outbreaks increased with increasing ability to respond to increased temperature (Björkman *et al.*, 2011). Kress *et al.* (2009) found a consistent relationship between temperature and Larch budmoth (LBM, *Zeiraphera diniana* Gn.) outbreaks. Björkman *et al.* (2011) again hinted that the frequency of favourable years of outbreaks is directly linked to the temperature variations.

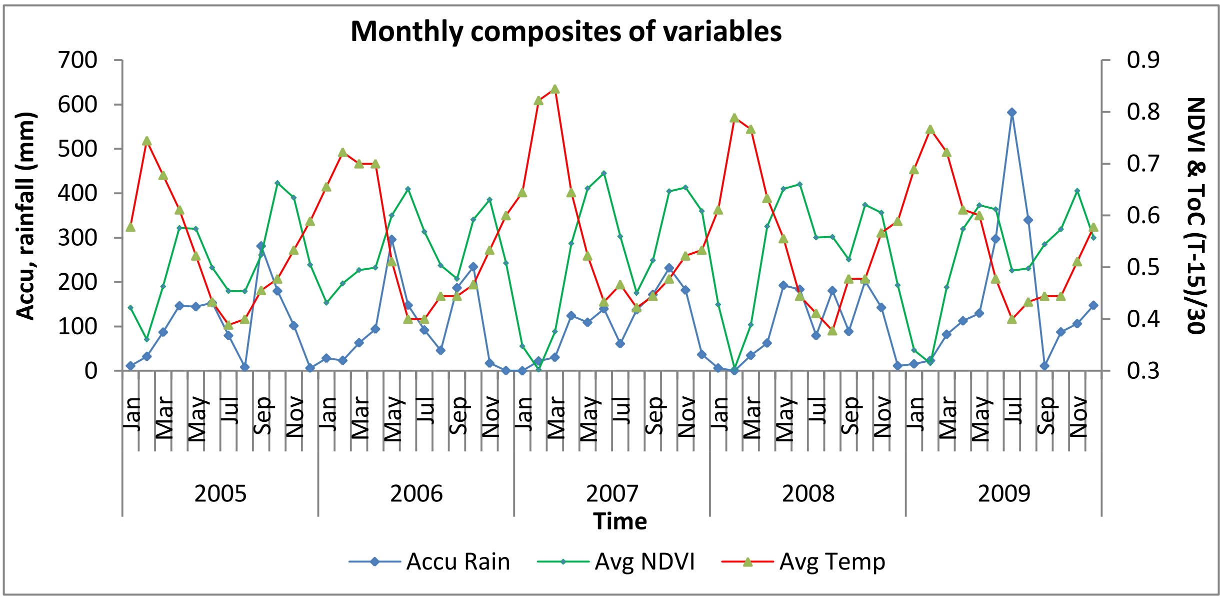

Figure 5:8 Time series of monthly composites of NDVI, rainfall and temperature

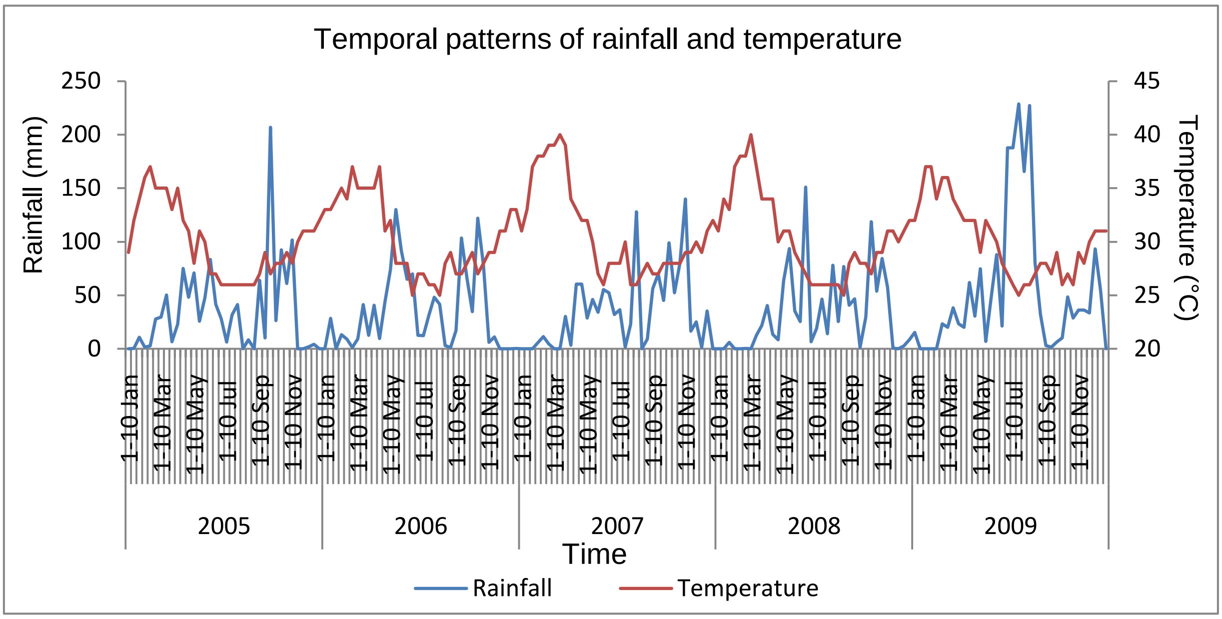

Figure 5:9 temporal patterns of rainfall and temperature

5.3. Regressing presence and absence of outbreaks with NDVI

Table 5-1 Summary output of stepwise logistic regression (Forward LR)

		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I.for EXP(B)	
								Lower	Upper
Step 1[a]	@2131Oct06	-.156	.040	15.557	1	.000	.855	.792	.924
	Constant	32.463	8.250	15.482	1	.000	1.255E14		
Step 2[b]	@2131Oct06	-.288	.094	9.308	1	.002	.750	.623	.902
	@2130Sep09	-.092	.040	5.432	1	.020	.912	.844	.985
	Constant	74.289	24.901	8.900	1	.003	1.833E32		

a. Variable(s) entered on step 1: @2131Oct06.
b. Variable(s) entered on step 2: @2130Sep09.
$P \leq 0.05$

Stepwise logistic regression was calculated and the result is shown in the table above. Out of the 18 temporal 10-day NDVI decades regressed across the minor season for 2006 and 2009, October 06 and September, 09 are significant at $p < 0.05$ and the final model is depicted below:

$$\text{Log}(p/1\text{-}p) = 74.289 - 0.288*21\_31\text{Oct06} - 0.092*21\_30\text{Sep09}$$

This indicates that the last dekad of the months of October and September in 2006 and 2009 respectively registered some disturbance in the vegetation composition of the district during the period; hence offer the most ideal conditions and therefore vulnerable months for outbreaks. This result could therefore be interpreted as possible outbreaks of the African armyworm as reported by the farmers interviewed

6. GENERAL DISCUSSION

The spatial distribution of armyworm outbreak in the Ejura-Sekyedumase district shows the concentration of outbreak locations in the predominantly savannah area. This area is grassland interspersed with maize cultivation and may be suitable for the insects. According to Rainey (Rainey, 1976) air temperature and certain crops attract insects to outbreak destinations. With no outbreaks occurring at the more vegetated area create natural windbreaks which disrupt the convergence of the insects (Johnson, 1969).

NDVI values of a whole growing season were constructed into trace profiles of crop growing conditions. These profiles indicate monthly variation of NDVI for the five year period. In this study the interpretation phase was mainly based on a qualitative analysis of NDVI temporal profiles calculated for observation points. For each observation, average NDVI value was calculated for each dekad and plotted on a graph (figure 5.8). Shapes and relative positions of each profile describe the development pattern of vegetation during the period. Also, accumulated monthly rainfall and mean temperature were extracted for same observation points. The temporal pattern of low NDVI for the months of October and September in 2006 and 2009 respectively are an indication of vegetation disturbance. This situation could not be due to drought since rainfall was fairly heavy during the period and therefore thought to be the effect of armyworm outbreak. This finding corroborate with Sudbrink *et al.* (2009) who reported lower NDVI values in remotely sensed data that represented zones of open and/or stressed canopy as a result of activities of the beet armyworm (*Spodoptera exigua*). Indication that beet armyworm infestations were associated with lower NDVI values. In another study, exceptionally high rainfall was related with decreased NDVI as a result of flooding (Wang *et al.*, 2003). The time series mean monthly NDVI plots as well as the z-score transformation results confirm the graphical visualization of temporal variability in the pattern of NDVI across the five year period investigated. The stepwise logistic regression yielded significant relationship between dekadal NDVI and outbreak for October 2006 and September 2009. This result with regard to September 2009 is strange in that the z-score transformation analysis albeit depict a low positive NDVI anomaly at the same time, it does not show a likely outbreak in September 2009. For 2006, enough clues gathered point to the fact the highly negative NDVI anomaly and positive anomaly in precipitation was as a result of activity by this moth species.

Although temperature and rainfall are essential to the development of the African armyworm, it is difficult to measure their risk to outbreaks (Hill and Atkins, 1983). The rainfall and temperature variability particularly at the onset of the minor growing season for 2006 suggest reasons which could probably have influenced attraction of the moth to the area. This assertion is based on the claim by Shank (1996) that changes in the climatic condition at the onset of the rainy season can give cause to outbreaks. Clearly, 2006 offer peculiar conditions for instance temperature was quite low coupled with moderate rainfall. Average temperatures close to 25°C at the beginning of the season enhance mating, oviposition and hatchability of eggs (David and Ellaby, 1975; Kanda and Oya, 1985). In contrast however, the pattern and variability of these climatic factors do not seem to follow a trend that suggest clues to associate with the low NDVI values recorded in September 2009. Wen and Zhang (2010) found a close relationship between the wide-area temperature, rainfall factors and the beet armyworm outbreak trend. A good spell of hot weather is conducive for armyworm survival since the larval duration decreases with increasing temperature (Pond, 1960).

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

In conclusion, it is gratifying to note that this study is a preliminary investigation and that the findings emanating will create more opportunities to unravel the problem of cyclic armyworm outbreaks in the transitional zone of Ghana. An attempt has been made to find a relationship between NDVI and armyworm outbreak. Variation in climatic patterns has also been suggested to account for the suitable condition required by the adult moth to establish a colony which subsequently leads to mass reproduction and destruction of crops. This study has been able to establish a link between temporal NDVI and outbreak of the African armyworm. The transition zone covers about a third of the land area of the country and the problem abounds in the entire zone. This study therefore should be antecedent to holistically investigate the problem of armyworm outbreaks in Ghana. Considering the entire transitional zone, several years of outbreaks as well as the availability of data covering a very long period could be accessed for analysis. The outcome of such an exercise should give a clear pattern to solve the problem. Admittedly, however, adequate justice has not been done to the topic as a result of the paucity of data. Five years data with only two years of occurrences are not adequate to fully investigate the outbreak status of this insect. It is also worthy of mention that the poor weather station facility in the study area is a big stumbling block for quality climate data. Climatic information in three pixels did not help as well. On the whole, this study has provided sufficient evidence for regional scale investigation.

7.2. Reccommendations

Since it just the beginning, it is recommended that further studies be conducted this time with the inclusion of climatic factors such as humidity, evapotranspirarion wind speed and wind direction and also cover a substantial portion of the zone if not all. Because of the difficulty to access gridded products of the above mentioned climatic factors emphasis should be placed on direct field measurements. Equally, the quality of field data collection should be improved

LIST OF REFERENCES

Agresti, A. (2002). *Categorical Data Analysis* (2 edition ed.). New York: Wiley-Interscience, 734 pages.

Allen, J.C., Kopp, D.D., Brewster, C.C., & Fleischer, S.J. (1999). 2011: An Agricultural odyssey. *American Entomol., 45*, 96-104

Altieri, M.A., Letourneau, D.K., & Risch, S.J. (1984). Vegetation diversity and insect pest outbreaks. *Critical Reviews in Plant Sciences, 2*(2), 131 - 169.

Andrewartha, H.G., & Birch, L.C. (1954). *The Distribution and Abundance of Animals*. Chicago, Illinois: The University of Chicago Press.

Anyamba, A., Tucker, C.J., & Mahoney, R. (2002). From El Niño to La Niña: Vegetation Response Patterns over East and Southern Africa during the 1997–2000 Period. *Journal of Climate, 15*(21), 3096-3103.

Björkman, C., Kindvall, O., Höglund, S., Lilja, A., Bärring, L., & Eklund, K. (2011). High Temperature Triggers Latent Variation among Individuals: Oviposition Rate and Probability for Outbreaks. *PLoS ONE, 6*(1), e16590.

Brown, E.S., Betts, E., & Rainey, R.C. (1969). Seasonal changes in distribution of the African armyworm, *Spodoptera exempta* (Wlk.) (Lep., Noctuidae), with special reference to eastern Africa. *Bulletin of Entomological Research, 58*(04), 661-728.

Bryceson, K.P., & Cannon, R. (1990). Acquisition and use of low-cost meteorological satellite data in the Australian Plague Locust Commission. *Computers and Electronics in Agriculture, 5*(1), 47-64.

Cardenas, R., Sandoval, C.M., Rodriguez-Morales, A.J., & Franco-Paredes, C. (2006). Impact of climate variability in the occurrence of Leishmaniasis in Northeastern Colombia. *Am J Trop Med Hyg, 75*(2), 273-277.

Chamberlin, J. (2007). "Defining smallholder agriculture in Ghana: Who are smallholders, what do they do and how are they linked with markets?". Background Paper 0006 for the Ghana Strategy Support Program (GSSP), International Food Policy Research Institute (IFPRI), Washington, D.C, USA.

Cheke, R.A. (1995). Potential rates of Increase of solitarious and gregarious phases of the African armyworm *Spodoptera exempta* (Lepidoptera: Noctuidae). *Ecological Entomology, 20*(4), 319-325.

Cheke, R.A., & Tucker, M.R. (1995). An evaluation of potential economic returns from the strategic control approach to the management of African armyworm *Spodoptera exempta* (Lepidoptera: Noctuidae) populations in eastern Africa. *Crop Protection, 14*, 91-103.

Chen, J., Jönsson, P., Tamura, M., Gu, Z., Matsushita, B., & Eklundh, L. (2004). A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky-Golay filter. *Remote Sensing of Environment, 91*(3-4), 332-344.

Ciancio, A., & Mukerji, K.G. (2007). Concepts for Plant Protection in Changing Tropical Environments (pp. 81-130).

Cronk, B.C. (2010). *How to Use PASW Statistics A Step-by-Step Guide to Analysis and Interpretation* (Sixth ed.). New York: Pyrczak Publishing.

Dalin, P., Kindvall, O., & Björkman, C. (2009). Reduced Population Control of an Insect Pest in Managed Willow Monocultures. *PLoS ONE, 4*(5), e5487.

Davenport, M.L., & Nicholson, S.E. (1993). On the relation between rainfall and the Normalized Difference Vegetation Index for diverse vegetation types in East Africa. *Int. Journal of Remote Sensing, 14*(12), 2369-2389.

David, W.A.L., & Ellaby, S. (1975). The viability of the eggs of the African armyworm, *Spodoptera exempta* in laboratory cultures. *Entomologia Experimentalis Et Applicata, 18*(3), 269-280.

Debien, A., Neerinckx, S., Kimaro, D., & Gulinck, H. (2010). Influence of satellite-derived rainfall patterns on plague occurrence in northeast Tanzania. *International Journal of Health Geographics, 9*(1), 60.

Dewhurst, C.F., Page, W.W., & Rose, D.J.W. (2001). The relationship between outbreaks, rainfall and low density populations of the African armyworm, *Spodoptera exempta*, in Kenya. *Entomologia Experimentalis et Applicata, 98*(3), 285-294.

Dickson, K.B., & Benneh, G. (1988). *A New Geography of Ghana*. London: Longman.

Doraiswamy, P.C., Sinclair, T.R., Hollinger, S., Akhmedov, B., Stern, A., & Prueger, J. (2005). Application of MODIS derived parameters for regional yield assessment. *Remote Sens. Environ, 97*(2), 192-202.

Drake, V.A. (1994). The influence of weather and climate on agriculturally important insects: an Australian perspective. *Australian Journal of Agricultural Research, 45*, 487-509.

Elewa, A.M.T. (2005). *Migration of organisms, Climate, geography and Ecology* Springer-Verlag, Berlin Heidelberg

FAO. (2005). *Fertilizer use by crop in Ghana*. Rome, Italy: Food and Agriculture Organization of the United Nations.
FAO. (2010). *Climate change implications for food security and natural Resources management in Africa* Paper presented at the Twenty-sixth regional conference for Africa Luanda, Angola.
Faure, J.C. (1943). Phase variation in the armyworm *Laphygma exempta* (Walk.). Dept. of Agric. Forest *South African Sci. Bull, 243*, 17.
Fleming, R.A., & Candau, J.-N. (1998). Influences of Climatic Change on Some Ecological Processes of an Insect Outbreak System in Canada's Boreal Forests and the Implications for Biodiversity. *Environmental Monitoring and Assessment, 49*(2), 235-249.
Fuhrer, J. (2003). Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change. *Agriculture, Ecosystems & Environment, 97*(1-3), 1-20.
Goetz, S.J., Prince, S.D., & Small, J. (2000). Advances in satellite remote sensing of environmental variables for epidemiological applications. In S. E. R. D. J. R. S.I. Hay (Ed.), *Advances in Parasitology* (Vol. Volume 47, pp. 289-307): Academic Press.
Green Bank, D.O. (1956). The role of climate and dispersal in the initiation of outbreaks of the spruce budworm in New Brunswick. *Canadian Journal of Zoology, 34*, 453-476.
Grzywacz, D., Mushobozi, W.L., Parnell, M., Jolliffe, F., & Wilson, K. (2008). Evaluation of *Spodoptera exempta* nucleopolyhedrovirus (SpexNPV) for the field control of African armyworm (*Spodoptera exempta*) in Tanzania. *Crop Protection, **27***(1), 17-24.
GSS. (2004). *Ghana Living Standard Survey Report Round Four, 1989/99* Ghana Statistical Service, Accra, Ghana.
Gunn, A., & Gatehouse, A.G. (1985). Effects of the availability of food and water on reproduction in the African army worm, *Spodoptera exempta*. *Physiological Entomology, 10*(1), 53-63.
Guppy, J.C. (1961). Life history and behaviour of the armyworm,*Pseudaletia unipuncta* (Haw.) (Lepidoptera: Noctuidae), in eastern Ontario. *Canadian Entomologist, 93*, 1141-1153.
Gutman, G. (1987). The derivation of vegetation indices from AVHRR data. *International Journal of Remote Sensing, 8*(8), 1235 - 1243.
Haggis, M.J. (1996). Forecasting the severity of seasonal outbreaks of African armyworm, *Spodoptera exempta* (Lepidoptera: Noctuidae) in kenya from the previous year's rainfall. *Bulletin of Entomological Research, 86*(02), 129-136.
Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Carroll, M., Dimiceli, C., & Sohlberg, R.A. (2003). Global percent tree cover at a spatial resolution of 500m: first results of the MODIS vegetation continuous fields algorithm. *Earth Interact, **7***, 1-15.
Harvey, A.W., & Mallya, G.A. (1995). Predicting the severity of Spodoptera exempta (Lepidoptera: Noctuidae) outbreak seasons in Tanzania. *Bull. Ent. Res, 85*, 479-487.
Hattingh, C.C. (1941). The biology and ecology of the armyworm *Laphygma exempta* and its control in South Africa. Dept. Agricult. Forest. *South African Sci. Bull, 217*, 50.
Hill, M.G., & Atkins, A.W. (1983). Incidence of the armyworm, *Mythima separata* Walker. (Lepidoptera: Noctuidae) and its introduced parasite *Apantheles ruficrus* Halliday (Hymenoptera: Braconidae) in maize. *New Zealand Journal of Agricultural Research, 26*, 135-138.
Holt, J., Mushobozi, W.L., Tucker, M.R., & Venn, J.F. (2000). *Modelling African Armyworm Population Dynamics to Forecast Outbreaks* Paper presented at the Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute 24-26 March 1999, Pretoria, South Africa. Natural Resources Institute, Catham, UK.
IFPRI. (2009). International Food Policy Research Institute. Climate change: Impact on agriculture and costs of adaptation. Retrieved 26/07/10, from http://www.ifpri.org/publication/climate-change-impact-agriculture-and-costs-adaptation
IPCC. (2007). Intergovernmental Panel on Climate Change. Climate change: Synthesis approach. Retrieved 28/05/2010, from www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf .
Janssen, J. (1993). *African armyworm outbreaks: why do they occur after drought?* : Landbouwuniversiteit te Wageningen
Johnson, C.G. (1969). *Migration and dispersal of insects by flight*. London: Methuen, 763p.
Kabissa, J.C.B. (2008). African Armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Encyclopedia of Entomology, 1*, 53-59.
Kanda, K., & Oya, S. (1985). Effect of temperature on mating and oviposition of the armyworm Pseudaletia separata Walker. *Bulletin of National Grasaaland Research Institute, 30*, 27-33.

Kelly, M., & Guo, Q. (2007). Integrated Agricultural Pest Management Through Remote Sensing And Spatial Analyses. In A. Ciancio & K. G. Mukerji (Eds.), *General Concepts in Integrated Pest and Disease Management* (pp. 191-207): Springer Netherlands.

Kennedy, R.E., Cohen, W.B., & Schroeder, T.A. (2007). Trajectory-based change detection for automated characterization of forest disturbance dynamics. *Remote Sensing of Environment, 110*(3), 370−386.

Kidwell, K.B. (1990). Global Vegetation Index User's Guide. *U.S. Department of Commerce/National Oceanic and Atmospheric Administration/National Environmental Satellite Data and Information Service/National Climatic Data Center/Satellite Data Services Division.*

Kiritani, K. (2006). Predicting impacts of global warming on population dynamics and distribution of arthropods in Japan. *Population Ecology, 48*, 5-12.

Kress, A., Saurer, M., Büntgen, U., Treydte, K., Bugmann, H., & Siegwolf, R. (2009). Summer temperature dependency of larch budmoth outbreaks revealed by Alpine tree-ring isotope chronologies. *Oecologia, 160*(2), 353-365.

Lunetta, R.S., Shao, Y., Ediriwickrema, J., & Lyon, J.G. (2010). Monitoring agricultural cropping patterns across the Laurentian Great Lakes Basin using MODIS-NDVI data. *International Journal of Applied Earth Observation and Geoinformation, 12*(2), 81-88.

Mitchell, T.D., & Jones, P.D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology, 25*(6), 693-712.

Mushobozi, W.L., Grzywacz, D., Musebe, R., Kimani, M., & Wilson, K. (2005). New approaches to improve the livelihoods of poor farmers and pastoralists in Tanzania through monitoring and control of African armyworm, *Spodoptera exempta. Aspects of Appl. Biol., 75*, 37-35.

Niemann, K.O., & Visintini, F. (2005). Assessment of potential for remote sensing detection of bark beetle-infested areas during green attack: a literature review. *Natural Resources Canada , Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Mountain Pine Beetle Initiative*(Working Paper 2005-02), 14 p.

Odiyo, P.O. (1979). Forecasting Infestations of a Migrant Pest: The African Armyworm Spodoptera exempta (Walk.). *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 287*(1022), 403-413.

Page, W.W. (1988). Varying durations of arrested oocyte development in relation to migration in the African armyworm moth, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bulletin of Entomological Research, 79*, 181-198.

Peacock, L., Worner, S., & Sedcole, R. (2006). Climate Variables and Their Role in Site Discrimination of Invasive Insect Species Distributions. *Environmental Entomology, 35*(4), 958-963.

Phillips, S.J., Anderson, R.P., & Schapire, R.E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling, 190*(3-4), 231-259.

Pinter, P., Hatfield, J., Schepers, J., Barnes, E., Moran, M., Daughtry, C., et al. (2003). Remote sensing for crop management. *Photogrametric Engineering & Remote Sensing, 69*, 647-664.

Pond, D.D. (1960). Life history studies of the armyworm, *Pseudaletia unipuncta* (Lepidoptera: Noctuidae), in New Brunswick. *Annals of the Entomological Society of America 53*, 661- 665.

Rahman, M.R., Islam, A.H.M., & Rahman, M.A. (2004). 'NDVI Derived Sugar cane area Identification and crop condition Assessment'. *Planplus, Vol.* ***2.*** *Urban and Rural Planning Discipline, Khula University, Bangladesh*

Rainey, R.C. (Ed.). (1976). *Insect Flight*. Oxford: Blackwell Scientific, 287p.

Rebetez, M. (1996). Seasonal relationship between temperature, precipitation and snow cover in a mountainous region. *Theoretical and Applied Climatology, 54*(3), 99-106.

Reperant, L.A., Fučkar, N.S., Osterhaus, A.D.M.E., Dobson, A.P., & Kuiken, T. (2010). Spatial and Temporal Association of Outbreaks of H5N1 Influenza Virus Infection in Wild Birds with the 0°C Isotherm. *PLoS Pathogens, 6*(4), 1 - 9.

Roschewitz, I., Gabriel, D., Tscharntke, T., & Thies, C. (2005). The effects of landscape complexity on arable weed species diversity in organic and conventional farming. *J. Appl. Ecol., 42*, 873-882.

Rose, D.J.W., Dewhurst, C.F., & Page, W.W. (1995). The bionomics of the African armyworm *Spodoptera exempta* in relation to its status as a migrant pest. *Integrated Pest Management Reviews, 1*(1), 49-64.

Rose, D.J.W., Dewhurst, C.F., & Page, W.W. (2000). *The African Armyworm Handbook: The Status, Biology, Ecology, Epidemiology and Management of Spodoptera exempta (Lepidoptera: Noctuidae)* (2 ed.). Greenwich, UK: Natural Resources Institute.

Rose, J.W., Dewhurst, C.F., & Page, W.W. (1997). *The African armyworm handbook. Desert Locust Control Organization for Eastern Africa, PO Box 4255,* . Addis Ababa, Ethiopia165pp.

Schmitz, C. (2008). *Maize production and markets in Ghana : the impact of agricultural policy and rising prices : a multi-market model approach.* MSc thesis Wageningen University, Wageningen.
Scotford, I.M., & Miller, P.C.H. (2005). Applications of spectral reflectance techniques in Northern European cereal production : A review. *Biosystems Engineering, 90*, 235-250.
Shank, R. (1996). *Status of the Armyworm Outbreak in Ethiopia in 1996 and Considerations for Forecasting Migrations* UNDP REPORT.
Shao, Y., Lunetta, R.S., Ediriwickrema, J., & Iiames, J. (2010). Mapping cropland and major crop types across the Great Lakes Basin using MODIS-NDVI data. *Photogrammetric Eng. Remote Sensing In press.*
Simmons, A.M. (1992). Effects of constant and fluctuating temperatures and humidities on the survival of *Spodoptera frugiperda* pupae (Lepidoptera: Noctuidae). *Florida Entomol., 76*, 333-340.
Singh, T.V.K., & Satyanarayana, J. (2009). Insect Outbreaks and Their Management. In R. Peshin & A. K. Dhawan (Eds.), *Integrated Pest Management: Innovation-Development Process* (pp. 331-350): Springer Netherlands.
Snow, R.W., Craig, M., Deichmann, U., & Marsh, K. (1999). Estimating mortality, morbidity and disability due to malaria among Mrica's non-pregnant population. *Bulletin of the World Health Organization, **77***, 624-640.
Steinbach, M., Tan, P.N., Kumar, V., Potter, C., & Klooster, S. (2002). Temporal data mining for the discovery and analysis of ocean climate indices. In the 2nd workshop on Temporal Data Mining at the 8th ACM SIGKDD International conference on knowlegde Discovery and Data Mining, 23 July 2002, Edmonton, Alberta, Canada.
Stenseth, N.C., Mysterud, A., Ottersen, G., Hurrell, J.W., Chan, K.-S., & Lima, M. (2002). Ecological Effects of Climate Fluctuations. *Science, 297*(5585), 1292-1296.
Sudbrink, D.L., Harris, F.A., Robbins, J.T., English, P.J., & Willers, J.L. (2009). Evaluation of remote sensing to identify variability in cotton plant growth and correlation with larval densities of beet armyworm and cabbage looper (Lepidoptera:noctuidae). *Florida Entomologist, 86*(3), 290-294.
Tan, S.-Y. (2007). The influence of temperature and precipitation climate regimes on vegetation dynamics in the US Great Plains: a satellite bioclimatology case study. *Int. J. Remote Sens., 28*(22), 4947-4966.
Tanzubil, P.B., & McCaffery, A.R. (1990). Effects of azadirachtin and aqueous neem seed extracts on survival, growth and development of the African armyworm, *Spodoptera exempta*. *Crop Protection, 9*(5), 383-386.
Thenkabail, P., Lyon, J.G., Turral, H., & Biradar, H. (2009). *Remote sensing of global croplands for food security, Taylor & Francis Series in Remote Sensing Applications*. Boca Raton, FL, 510 pp: CRC Press.
Tucker, C.J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Rem Sens Environ, 8*, 127-150.
Tucker, M.R., & Pedgley, D.E. (1983). Rainfall and outbreaks of the African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bulletin of Entomological Research, 73*, 195-199.
Tucker, M.R., & Pedgley, D.E. (1983). Rainfall and outbreaks of the African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bulletin of Entomological Research, 73*(2), 195-199.
Udelhoven, T., Stellmes, M., del Barrio, G., & Hill, J. (2009). Assessment of rainfall and NDVI anomalies in Spain (1989–1999) using distributed lag models. *International Journal of Remote Sensing, 30*(8), 1961 - 1976.
Wang, J., Price, K.P., & Rich, P.M. (2001). Spatial patterns of NDVI to precipitation and temperature in the central Great Plains. *International journal of remote sensing, 22*(18), 3827 - 3844.
Wang, J., Rich, P.M., & Price, K.P. (2003). Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *International journal of remote sensing, 24*(11), 2345 - 2364.
Webster, R., & Oliver, M.A. (2007). *Geostatistics for environmental scientists*. Chichester Wiley.
Weiss, J.L., Gutzler, D.S., Coonrod, J.E.A., & Dahm, C.N. (2003). Seasonal and inter-annual relationships between vegetation and climate in central New Mexico, USA. *Journal of Arid Environments 57*, 507-534.
Weisz, R., Fleischer, S., & Smilowitz, Z. (1995). Site-specific integrated pest management for high value crops: sample units for map generation using the Colorado potato beetle (Coleoptera: Chrysomelidae) as a model system. *Journal of Economic Entomology, 88*, 1069-1080.
Wen, L.-Z., & Zhang, Y.-J. (2010). Modelling of the relationship between the frequency of large-scale outbreak of the beet armyworm, *Spodoptera exigua* (Lepidoptera: Noctuidae) and the wide-area temperature and rainfall trends in China. *Acta Entomologica Sinica, 53*(12), 1367 - 1381.
Woiwod, I. (1997). Detecting the effects of climate change on Lepidoptera. *J. Insect Conserv., 1*, 149–158.

Wulder, M.A., White, J.C., Coops, N.C., Han, T., & Alvarez, M.F. (2005). A protocol for detecting and mapping mountain pine beetle damage from a time-series of Landsat TM or ETM+ data. Report prepared for the British Columbia Ministry of Forests and Range. In (p. 70): Natural Resources Canada : Canadian Forest Service.

Zhang, M., Qin, Z., Liu, X., & Ustin, S.L. (2003). Detection of stress in tomatoes induced by late blight disease in California, USA, using hyperspectral remote sensing. *International Journal of Applied Earth Observation and Geoinformation, 4*, 295-310.

Appendix 1 Data sheet/Crop calendar questionnaire

African Armyworm outbreak Assessment in the Ejura-Sekyedumase District in the Transitional zone of Ghana

1. Sample No.……………………………… Location……………………………………
2. Lat…………………………….................... Lon…………………………………………
3. Respondent (Farmer/Trader/ Ministry staff)……………………………....................................
4. Years at location…………………………… Outbreak status…………………………….

Year	# acres Maize	Jul	Aug	Sep	Oct	Nov	Dec	Jan	EY bags	YL bags
2010										
2009										
2008										
2007										
2006										
2005										

LP- Land Preparation P-Planting RP-Replanting

AA-Armyworm Attack H-Harvest

S-Spray If sprayed, by whom whole field?

Insecticide used Effectiveness

Remarks:

Appendix 2. Legend descriptions of Land cover of study area

CCSW	=	closed cultivated savannah woodland (>20 trees/ha)
CSW	=	closed savannah woodland (>25 trees/ha)
MCTCC	=	moderately closed tree (>15 trees/ha) canopy with herb and bush
MDBST	=	moderately dense herb/bush with scattered trees (<15 trees/ha)
OCSW	=	open cultivated savannah woodland (11-20 tress/ha)
OF	=	open forest (<60%)
PC	=	planted cover
RSV	=	riverine savannah vegetation
WOCSW	=	widely open cultivated savannah woodland (6-10 trees/ha)