MAPPING AND MODELLING OF *Mimosa pigra* EXPANSION IN LOCHINVAR NATIONAL PARK, ZAMBIA

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MAPPING AND MODELLING OF *Mimosa pigra* EXPANSION IN LOCHINVAR NATIONAL PARK, ZAMBIA

by

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Disclaimer

Dedicated to
My beloved parents

Abstract

Invasions of native plant communities by woody aliens are occurring worldwide which represent a threat to the composition and diversity of the resident communities. Wetlands are especially vulnerable to invasions. In Australia 800Km^2 of floodplain and swamp forests have been completely invaded by a prickly tropical shrub, *Mimosa pigra*. Lochinvar National Park in Kafue river floodplain, a Ramsar site, rich and unique in terms of biodiversity is facing a threat of invasion by the woody alien *Mimosa pigra*. It is unknown how the shrub reached the area as early as 1950's and is now rapidly spreading in the Park converting the productive floodplain grasslands to monotypic impenetrable tall shrub lands which have a detrimental effect on the native flora and fauna.

Multitemporal datasets from LANDSAT and ASTER allowed us to map the extent of *Mimosa pigra* infestation in 1984, 1994 and 2005. The sequential mapping showed the direction and spatial pattern of invasion by *Mimosa pigra*. The first infestation of *Mimosa pigra* was sighted in 1980 along Nampongwe delta on the eastern side of the Park from where it started to expand to the floodplains over the years. It is now found widespread within the Park covering an area of about 2900 ha, the two big concentrations found on the western and eastern sides of the Park. The stochastic modelling technique known as Markov chain was used to examine whether it was possible to predict the expectable invasion zones of *Mimosa pigra* in the next 10 years. The study demonstrated that there has been an explosion of *Mimosa pigra* within the Park over the last 10 years preceded by a slow expansion in the previous decade. The floodplain grasslands have dramatically decreased by 3257.6 ha over a period of 20 years**.** The most evident reason for *Mimosa pigra* invasion within the Park after a lag period of 50years is the change in natural flooding regime after the construction of the Ithezi-tezhi dam which has affected the extent of flooded area and altered the growth of natural vegetation. Tests of independence between the different land cover images and test of Markovian dependence were performed in order to determine whether the process of *Mimosa pigra* expansion over the years was Markovian or not and to estimate if the predicted transition probabilities to the future was reliable. Markovian process assumes stationarity and statistical analyses proved that the pattern of change of land cover change in the Park was sudden and abrupt that the phenomenon under consideration was not Markovian.

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1. Introduction

1.1. Background

Biological invasions and the presence of exotic species are a pervasive and costly environmental problem (Vitousek *et al.*, 1996) that has been the focus of intense management activities over the last decades (Mooney & Drake, 1987). Alien species (also called non-indigenous species) invasion is a profuse problem in some of the most biologically sensitive zones of the world. The reason for such plants being invading and establishing themselves in regions that were once abodes of indigenous and endemic species can be attributed to various reasons such as continuing anthropogenic related disturbances, such as land conversion, grazing, and habitat fragmentation, combined with international trade and climate change indicate that these trends are likely to continue (Zedler & Kerceher, 2004). In this context, the major challenge for land managers and ecologists is how to effectively manage non-native plants to preserve native biodiversity. Various studies conducted on invasive aliens prove that once they start expanding the area little can be done to eradicate them. However being able to delineate the spatial extent and to ascertain the severity or intensity of the invasion is essential for resource management (Byers *et al.*, 2002).

Various definitions can be found for invasive species. The Plant Conservation Alliance (2004) defines it as follows: ‘an organism is considered exotic (alien, foreign, non indigenous, non-native) when it has been introduced by humans to a location(s) outside its native or natural range. A naturally aggressive plant may be especially invasive when it is introduced to a new habitat. An invasive species that colonizes a new area may gain ecological edge since the insects; diseases and foraging animals that naturally kept its growth in check and its native range are not present in its new habitat. In the past, such spread was controlled by the presence of the vast oceans and high mountains of the world that effectively separated ecosystems; any such spread to occur was only through natural carriers such as wind, water, birds and wild animals. As humans increased their geographic knowledge and ventured to the high seas, cut roads across lands and flew over mountains, then was born an era of uncontrolled spread of alien species, both knowingly and unknowingly. These species can have adverse economic impacts by reducing crop yields or the quality of grazing lands and can have negative ecological impacts including reducing biodiversity, endangering rare communities and altering processes such as nutrient cycling (Higgins *et al.*, 1999; Vitousek, 1990; Young & Longland, 1996). An invasive plant is one which establishes over large areas and persists. Invasiveness is characterised by robust vegetative growth, high reproductive rate, abundant seed production, high seed germination rate, and longevity.

There are several known spreads of invasive species that posed serious management problems to concerned ecologists. Lowe *et al* (2003) provides a list of world's 100 worst invasive species. The booklet also states that "History is rich with tales of the disastrous outcomes of some intentional introductions such as that of the Nile Perch, which resulted in the extinction of more than 200 other fish species". Invasive alien plants such as Water Hyacinth (*Eichornia crassipes*), Salvinia (*Salvinia molesta*), Giant mimosa (*Mimosa pigra*) and Lantana (*Lantana camara*) have established themselves in freshwater and terrestrial ecosystems throughout Asia (Bambaradeniya, 2002; Napompeth, 2003). Invasive species are generally more resistant to climatic fluctuations and management efforts rarely find absolute success in tackling them. Studies conducted on control of *Chromolaena odorata* in South Africa shows that the efficacy and modification of treatment protocols seldom results in local pest eradication (van Gils *et al.*, 2004). Prevention, early detection, and efficient management are the most cost-effective means of reducing the problems caused by invasive plant species worldwide (Byers *et al.*, 2002).

1.2. General description of *Mimosa pigra*

Mimosa pigra is an invasive weed, geographically distributed worldwide especially in South East Asia, Australia and east Africa as shown in figure 1.1 (a) and (b).

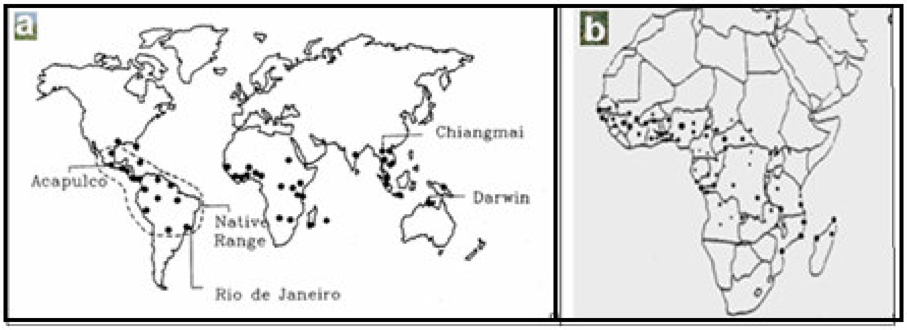


Figure1. 1a) Map showing the global distribution of *Mimosa pigra*
b) Map showing the distribution of *Mimosa pigra* in Africa
(Source-CSIRO, Australia)

Mimosa pigra has the potential to spread through natural grassland floodplain ecosystems and pastures, converting them into unproductive monospecific tall scrubland that sustains lower levels of biodiversity. In Thailand *Mimosa pigra* blocks irrigation systems that supply rice fields, reducing crop yield and harming farming livelihoods. In Vietnam it has invaded unique ecosystems in protected areas, threatening the biodiversity of seasonally inundated grasslands. In the Northern Territory of Australia it has completely invaded about 80,000 ha of floodplains and marshes over a 700 km arc altering the hydrology of the wetlands and causing a gross change of the vegetation structure. It is known as Australia's worst weeds because of its potential for spread invasiveness, economic and environmental impacts. It has been described as the Weed of National Significance.

Mimosa pigra also known as catclaw mimosa or giant sensitive plant, is a thorny upright scrambling woody shrub that grows up to 2 to 6 m in height as shown in figure 1.2.(a). The shrub is supported by extensive lateral roots with numerous fine roots that have occasional nodules. Large thorns up to 7mm are found on the stem with smaller thorns on the branches between the leaves. The leaves are fern like and fold together when touched are made up of fine leaflets and occurs in pairs along branches. Each flower head produces between 10 and 20 olive green seed pods, 60–80 mm long, which turn brown and break into segments when mature as shown in figure 1.2.(b) (c) and (d). Each segment contains an oblong-shaped seed, 4–6 mm long and 2 mm wide (CSIRO, 2002). The seed segments, which are covered with many fine hairs, float on water and adhere to clothing or hair

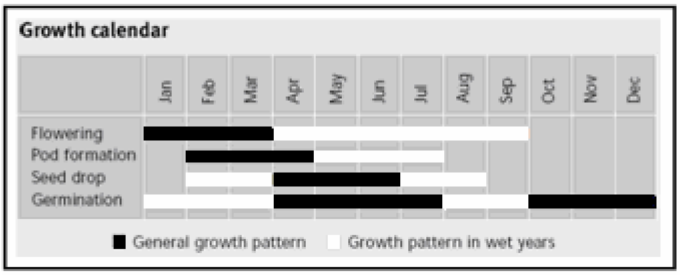
Ecology

The species is highly intolerant of shade and favours wet dry tropical climate. It requires full sunlight to flower and fruit and nearly full sunlight to survive. The two principal ingredients for successful establishment are moist or wet soils and disturbance that allows full sunlight. It is a fierce competitor with low vegetation and one of the few shrubs capable of succeeding in dense, tall grass swards. It tolerates a wide variety of soil conditions, short-term flooding, seasonal drought, and grows at elevations from near sea level to 700 m (Janzen, 1983). Although it grows mixed with other vegetation in its native habitat, the species forms pure stands with little understorey in many of its exotic habitats (Pacific Island Ecosystems at Risk, 2002).

Figure1. 2 - Photographs of *Mimosa pigra* a) Adult plants b) Flower heads and c) Young d) Mature seed pods (Source- CSIRO, Australia)

Reproductive biology

Mimosa can germinate all year round if the soil is moist but not flooded. However most germination takes place at the end of wet season as shown in table 1. Growth in seedlings is rapid, and flowering occurs between 4 and 12months after germination. The main flowering season is January –March but flowering can be extended into the dry season under moist conditions. One average plant can produce more than 9,000 seeds annually (Lonsdale, 1992). Large plants can produce up to 220,000 seeds per year. Seeding occurs approximately five weeks after flowering and fruits ripen after about three months. Most seeds germinate when first wetted although a tough, impermeable coating allows some seeds to remain viable in sandy soil for over 20 years. The pod segments disperse by floating on water and clinging to clothing and possibly animal fur and feathers (Janzen, 1983). Mimosa can grow extremely quickly and can double in infestation, in ideal conditions infestations double in size every 18 months.



Growth calendar

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flowering	■	■	■	□	□	□	□	□	□			
Pod formation		■	■	■	□	□	□					
Seed drop		□	□	■	■	■	□	□				
Germination	□	□	□	■	■	■	■	□	□	■	■	■

■ General growth pattern □ Growth pattern in wet years

Table1. 1-Table showing the reproductive cycle of *Mimosa pigra*
(Source-CRC Weed Management, 2003)

Advantageous feature of Mimosa

Mimosa has many features that are considered to be advantageous and thus aiding in its successful establishment.

1. Mimosa can withstand the anaerobic conditions of inundation and flooded soils by sprouting adventitious roots near the surface where they can take up oxygenated water (Miller *et al,*. 1981).

2. If chopped down, mimosa will easily resprout from the stump (Wanichanantakul and Chinawong, 1979). If mimosa is burnt, the foliage may become desiccated and fall, but up to 90% of mature plants and up to 50% of seedlings may regrow.

3. The plants mature quickly and can set seed in their first year of growth (Lonsdale *et al,*. 1985). The seedpods are covered with bristles that enable them to adhere to animals and clothing, and to float on water for extended periods (Miller *et a,*. 1981). The seeds are also dispersed in soil and mud, adhering to vehicles and other machinery (Lonsdale *et al,* 1985). Livestock and native animals sometimes graze mimosa plants (Miller, 1988) and pass the seeds in their dung (Miller & Lonsdale, 1987).

4. The lifespan of the seeds in the ground depends greatly on their depth in the soil and the soil type, and may be up to 23 years in sandy soils (Lonsdale, 1992).

5. Seed rate production has been measured between 9,000 and 12,000 m^2 per year depending on the conditions (Lonsdale & Abrecht, 1988). The most productive plant observed in the field produced about 220,000 seeds per year (Lonsdale, 1992).

6. Under the right conditions, mimosa grows quickly at a rate of about 1 cm per day, and infestations can double in area in one year. It can also withstand droughts (Lonsdale, 1993).

7. Mimosa has low nutrient requirements and consequently can grow within a wide range of soil types including nutrient-poor sands, alluvial red and yellow earths, silty loams and heavy black cracking clays (Miller, 1983).

1.3. Problem statement

The Kafue flats are one of the most biologically diverse ecosystems in Zambia and comprise complex patterns of lagoon, marshes and floodplain grassland that provide habitat for a wide range of wildlife (Acreman *et al.*, 2000). It is one of the few remaining habitats for the increasingly endangered bird species of Wattled Cranes *(Bugeramus carnculatus)* also a home for one of a rare antelope, Kafue Lechwe *(Kobusleche kafuensis),* a threatened and endemic species

Mimosa pigra thorny shrub native to Mexico and Central and South America has become a dominant species in the Lochinvar National Park over the last 15 years (Chabwela & Mumba, 1998). It is unclear how the plant has been introduced to Africa but it has dramatically spread to form monotypic stands over the floodplains. It forms dense impenetrable thickets which exclude native plants and animals, transforming sedgeland and grassland on flood plains into tall shrub-lands. There is anecdotal evidence that mimosa infestation has affected the ecology of bird and mammal life thereby displacing the big fish eating birds like Pelicans and Storks which feeds on the shallow waters and the open and muddy waterline (IUCN, 2003). It has also been responsible for the loss of lekking and grazing lands for the Kafue lechwe. It is a woody perennial shrub with a deep tap root and can tolerate harsh environmental conditions ranging from seven months of dry season to flooding in wet season. A single plant within an average stand can produce 9000 seeds annually which fall mostly between mid wet season and mid dry season. As a biological invasion, the existence and spread of mimosa could lead to detrimental consequences in the floodplain ecosystem through the alteration of resource utilization, modification of the trophic structure or even changes in the disturbance regime (Lonsdale, 1983). Mimosa could establish itself over other species and eventual remove them from the ecosystem; such effects are noticed else where in the world. In Australia mimosa invaded 80,000 ha of ecologically and economically valuable wetlands and replaced native species (Braithwaite *et al.*, 1989). Such changes within the Kafue Flats could severely impact the services for which this wetland is valued in particular food and habitat support for wildlife.

Before 1980 there was only one infestation occupying approximately 2 ha at the head of the Nampongwe stream, which flows through Chunga Lagoon as shown in figure 1.3 (b) and (c), although it had previously been recorded on levees bordering the Kafue River (Douthwaite & van Lavieren, 1977). In 1986 it covered approximately 100 ha (Thompson, 1986) whilst a survey undertaken in 2003 shows that this area has since increased to around 2,500 ha as shown in figure 1.4 . Unlike the lower stretch of the Kafue Flats no studies has been done so far in Lochinvar on the invasives affecting the area .This demands a scientific attention to the growing problem, especially from a geo-information point of view, as it enables integration of available data, back-cast and forecast in a single platform, easing the work of further management propositions.

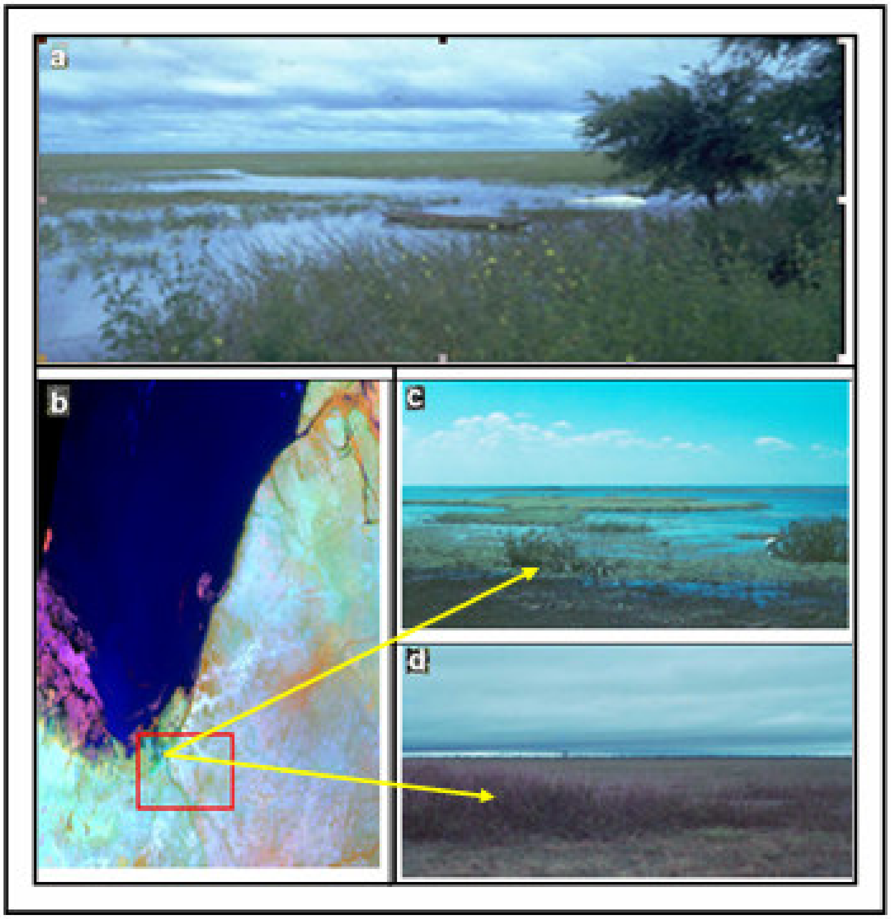


Figure 1. 3- a) Floodplains of Lochinvar National Park in 1973 when there was no mimosa b) Nampongwe delta from where the mimosa infestation first began c) Nampongwe delta in 1983 where the first mimosa plants were sighted d) Mimosa pigra expanding along the Nampongwe delta in 1985
(Courtesy- Geoffery Howard, 2006)

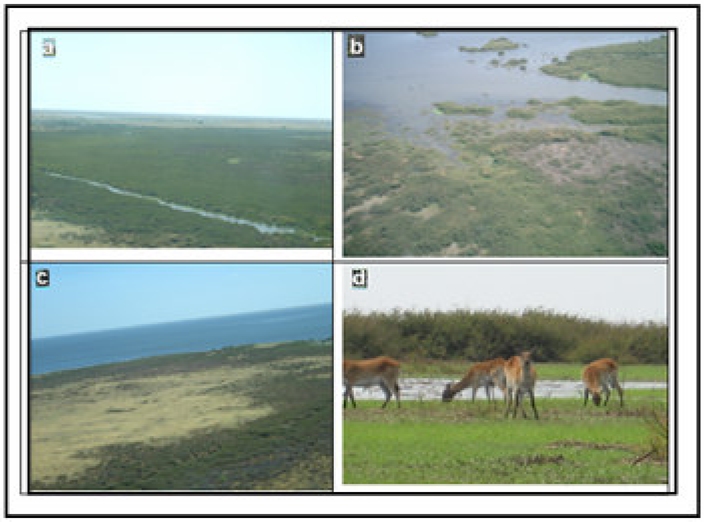


Figure 1. 4-(a) (b) and (c)- Aerial view of the infestation of *Mimosa pigra* in Lochinvar National Park d) Mimosa pigra infestation on the grazing grounds of Kafue Lechwe

The most viable method of surveying such profuse growth of invasive species in a Savannah desert climate as of Zambia is particularly successful when using multi-spectral satellite remote sensing data. Owing to the large number of cloud free datasets (as against the tropical parts of the world), the use of multi-spectral data, though from multiple sensors, allows to map the various land cover classes and predict the probability of changes from one class to another over years. Absolute changes in land use and land cover are not measurable as a continuous phenomenon owing to the complex processes involved. However, it is possible to identify the evolution of such changes from available continuous satellite datasets. Such satellite data sets provide time frozen instances of the changes occurring, enabling to estimate the probabilities of changes from one instance to the other and from one class to the other. The calculated a priori probability can be postulated for predictions. Such predicted probabilities can be used to back cast and forecast the occurred/possible changes. The derived results can be used for futuristic applications in management planning. Remote sensing and GIS based change detection studies have predominantly focused on providing the knowledge of how much, where, what type of land use and land cover change has occurred, however few of them also address the questions how and why. Owing to the complexity of modelling land use/ land cover changes as continuous process, most of the researchers have resorted to the assumption that land use/land cover changes of a given region are a stochastic process (Brown *et al.*, 2000; Fischer & Sun, 2001; Morisette *et al.*, 1999). Markovian Model is an ideal method for such an attempt, given the fact that the method considers change as a stochastic phenomena, with future probabilities of changes depended on the predicted transitional probabilities from known changes.

1.4. General description of Markov chain models

A Markov chain is a mathematical model for describing a certain type of process that moves in a sequence of steps through a set of states (Lambin, 1994). For land-cover change, the states of the system are defined as the amount of land occupied by various land covers. The number of possible states is either finite or denumerable (Idrisi, 2005). While it is clear that the actual process takes place in continuous time, it is almost impossible to apply a continuous time model to any but the simplest phenomenon. It is therefore, more convenient to regard the process as one which is discrete in time (Bell, 1974). When Markov analysis is used the matrix of changes is a transition matrix of conditional probabilities reflecting the probability of change from one class at a time t to another class at a time t+1. It involves the graphical locational display of pixels' likelihood of experiencing a change into a specified sate in accordance with a matrix of transition probabilities which involves probability mapping (Logsdon *et al.*, 1996).

This approach can be applied to any set of spatially coterminous data sharing a common classification system. Conterminous simply means that the state or class of a specific pixel can be compared with the same pixel's class at another time (Logsdon *et al.*, 1996). Markov chains represent a dynamic system of special classes involving transition probabilities, described as symmetric matrices (Logofet & Lesnaya, 2000). Here the focus is to demonstrate an application that estimates probabilistic behaviour of land cover changes. Therefore we assume the data to be comparable on a pixel by pixel basis and that the classification system correctly labels the objects in space to the future (Logsdon *et al.*, 1996).

The central mechanism of a Markov chain is a probability P_{ij} which refers to the transition or movement from a state i to a state j in a given time interval, where *i* and *j* are either locations to model spatial diffusion processes or locationally relevant classes to model landscape changes (Brown, 1970). For land use change studies, the states of a system are defined as the amount of land covered by various land cover classes, measured as percentages of the area of each landscape unit. For discreet landscape models, the Markov model can be expressed, in matrix notation, as

$n_{t+1} = M\, n_t$……………………………………………………………………………eqn **1**

where n_t is a column vector , $n=(n_1,n_2 \ldots n_m)$, whose elements are the fraction of land area in each of m states at a time t, and M is an m x m matrix whose elements, P_{ij} are the transition probabilities during time interval from t to t+1. The model thus calculates an output distribution of land area among states from initial configuration, by means of transition matrix. The markov chain describes an area in aggregate terms i.e. it is a distributional landscape model. Thus we shall be able to say that given current trends , it looks as if the different land uses in a landscape area will be in the proportions predicted by the Markov model (Bell, 1974). In a markovian process, model output, which is the distribution among state, is based on transition probabilities. These reflect transition characteristics such that

$P_{ij} = f(a_i, b_j, c_{ij})$……………………………………………………eqn **2**

Where P_{ij} is the probability of change between the states i and j as a function of characteristics of the state of origin a_i, characteristics of the output state b_j and some relationships between the states of origin and output c_{ij}.

The attractiveness of Markov chain analysis is that the models parameters are easily estimated. The transition probabilities can be statistically estimated from a sample of transitions occurring during some time interval. Given a_{ij} indicating transitions between pairs of states over some time interval, the transition probabilities P_{ij} are readily estimated as

$P_{ij} = a_{ij}/\Sigma_j\, a_{ij}$…………………………………………………………………eqn **3**

The initial probability vector and the transition matrix completely determine the Markov chain. However the Markov model has several assumptions as stated below

1) To regard land use and land cover as a stochastic process, and different categories are states of a chain (Stewart, 1994).

2) Markov chain is a first-order process, which means that the probability of a particular set of outcomes depends only on the current distribution among states and the transition probabilities, so that history has no effect. Though there are higher

orders markov chains that can be applied to predict the land cover changes it has not been considered in this study.

3) Markov regards the changes as a stationary process.

.Suppose that an area is characterised by a single species or species group i at some time t. Between an observation at time t and a subsequent observation at time t+1, the area can either remain in species i or can change to some other species j. The probability of transition is stationary if the values of P_{ij} do not change over time. The process is Markov if the probability of transition from state i to state j does not depend on a particular path taken to arrive at a state i (Feller, 1968).

Consider a row vector n_t whose elements are the number of plots in each of the m species at time t. If the Markov and stationarity and markov assumptions are made, then the transition models can be expressed as

$$n_{t+1} = n_t P \text{.. eqn } \mathbf{4}$$

Where P is a matrix whose elements are P_{ij} (probability of transition from state i to state j) discussed above. The matrix P is a row- standardized, such that the sum of transition probabilities from a given state is always equal to one. The value of the approach is that the transition matrix , once specified , can be used analytically to project future landscape compositions (Jahan, 1986). Thus we have a method for projecting vegetation composition over time given an initial distribution of plots among species no.

Since

$$n_1 = n_o P \text{.. eqn } \mathbf{5}$$

1.5. Literature review

Mapping invasive species is critical to the successful management of bio hotspots. Mapping them with absolute accuracy is yet a hypothetical proposition owing to various reasons however an attempt to identify and delineate the actual spread of invasive species needs to be explored. Techniques, such as remote sensing, offer significant opportunities for providing timely information on invasions of non-native species into native habitats. In contrast to field based surveys, imagery can be acquired for all habitats, over a much larger spatial area, and in a short period of time. Consequently, researchers have sought to exploit unique phenological, spectral, or structural characteristics of the non-native species in the image to distinguish them from the mosaic of species around them. In contrast; the use of digital multispectral imagery offers the opportunity for automated image processing, access to recent historical data for time series analyses, and large spatial coverage. Some studies have had success even using coarse-resolution (1.1 km pixel) advanced very high resolution radiometer (AVHRR) imagery to identify weeds. For example,(Peters *et al.*, 1992) identified moderate to heavy infestations of broom snakeweed (*Gutierrezia sarothrae*) with an average cover > 9% in a 4_4 km site. This species was distinguished from grasslands using the normalized difference vegetation index (NDVI)(Tucker, 1979) due to differences in phenological activity. However, being able to delineate the spatial extent and to ascertain the severity or intensity of the invasion is essential for resource management (Byers *et al.*, 2002). It is necessary for administrators to have an insight into the future changes that may come about in biologically critical areas. In order to prevent invasions and target monitoring efforts more effectively, we thus need to forecast locations at the greatest risk of invasions (Holway *et al.*, 1998). Managers require accurate and timely spatial information to assist with locating and controlling small infestations before they grow too large to eradicate effectively (Naylor *et al.*, 2005)and to monitor the effectiveness of their management strategies (Cooksey & Sheley, 1997).

In-order to forecast one needs to know the past and thus a back-casting and forecasting of the actual spread and invasion of the species is necessary. Several attempts of mapping invasive species can be found in literature. Joshi *et al.*, (2006) uses an indirect, remote sensing based method to map the invasion of *Chromolaena odorata* in the understorey of Nepal's forests. Ripley (2003) details the method of mapping *Codium fragile*, in Nova Scotia, Canada using hyperspectral data. Underwood *et al.*, (2003) and Lawrence *et al.*, (1999) reports the use of different methods of processing hyperspectral imagery for mapping invasive species. Hill *et al.*, (1998) explains an algorithmic model implemented in a GIS interface to evaluate the propagation of the green alga of tropical origin *Caulerpa taxifolia* in the north-western Mediterranean sea. van Gils *et al* (2006) used ASTER, GPS and GIS for mapping the invasive alien *Chromolaena odorata* in South Africa. A more traditional, field based method of invasive species distribution assessment is detailed by Rooney (2005). Stephenson *et al.*, (2006) describes the use of logistic regression with spatial autocorrelation based models for predicting the spread of *Rhododendron ponticum* in British Isles. Austin (2002) details several theoretical and practical concerns of predicting species distribution. Invasion of a species and its distribution as dominant over indigenous species are clearly noticeable in the spectral behaviour of a region, thus enabling a remote sensing satellite data set based approach towards mapping land cover changes which eventually will enable the quantification of changes that have occurred. Such an approach can provide the possibilities of change from natural vegetation cover to an invasive species dominant cover, if approached in a probabilistic manner. Over the last few decades, a range of models of land cover change have been developed to meet land use management needs and to better assess and project the future role of land use and land cover change in the functioning of the earth system (Veldkamp & Lambin, 2001). Aspinall (2004) used generalized linear models for land use/land cover change analysis in Gallatin Valley, Montana. Li and Yeh, (2002) used neural network based cellular automata implementation in GIS for predicting multiple land use changes. Weng (2002), Petit *et al*., (2001), Brown *et al*., (2000) are few of those who used Markovian Modelling to examine the stochastic nature of the land use and land cover change data and to project the stability of future land development.

In this study Markov modelling has been chosen for various reasons. The patterns of landscape development in time and space are the result of complex interactions of physical, biological, and social forces. Most landscapes have been influenced by human land use, and the resulting landscape mosaic is a mixture of natural and human-managed patches that vary in size, shape, and arrangement (Burgess & Sharpe, 1981; Forman & Godron, 1986; Krummel *et al.*, 1987). The majority of research utilizes regression-based approach, which relates the locations of land use and land cover change to a set of spatially explicit variables, and uses models such as logistic (Landis, 1994; Turner, 1987; Wear *et al.*, 1998) and hedonic price models (Geohegan *et al.*, 1997).

Spatial transition-based models often refer to cellular automaton simulation models, which allow for predicting future land development based on probabilistic estimates with Monte Carlo or other methods (Clarke *et al.*, 1997). One crucial limit to the development of the process models is, however, the deficiency of explicit modelling tools for change processes in the current generation of remote sensing and GIS systems(Clarke & Gaydos, 1998). Equally important is the issue of data availability (Baker, 1989). Another characteristic of many land use change models is that they are not independent executables but an integrated component of a larger model that may include demographic, ecological, economical, and hydrological modules as well. Whilst it is quite common to simulate land use changes along with dynamics of other ecosystem components, it may be quite cumbersome to use a complex integrated model if one only needs a systematic method for generating a set of different land use patterns rather than the entire array of model capabilities and model outputs (Weng, 2002). Markov processes offer a potential advantage here. Markov analysis of land use change is an aggregate, macroscopic approach because it does not directly account for any of the drivers of land use change (Brassoulis, 2000). This being a probabilistic model, an important advantage in terms of land use change is that land use dynamics can be analyzed at a watershed or regional scale instead of dealing with every plot at the scales where land use changes actually occur, the farm and field levels. This makes these models particularly useful when dealing with uncertainty about the complex processes and relationships between biophysical, economic, and social-cultural factors that affect land use changes.

There are numerous applications of Markov processes for modeling dynamics in land use and vegetation (Balzter, 2000; Logsdon *et al.*, 1996). The stochastic approach offered the advantage that land use dynamics could be simulated at a watershed level without having to describe the complex relationships between biophysical, economic and human factors that affect land use decisions at the farm and individual field level.

A stochastic process as opposed to deterministic ones is governed by random variables and describable only in probabilistic terms. A deterministic model does not take into account of random variation and therefore gives a fixed and precisely reproducible result. Probabilistic models in general are appropriate for those processes where there is complexity of relationships between the interacting variables, poor understanding of driving forces and unpredictable character of ecological consequences for human decision making (Lambin, 1994). Given the difficulties in designing deterministic models, it is convenient to treat these processes as random in aggregate, and to include them in this form in some stochastic process describing landscape structure. This approach has become common in ecology and geography, to model landscape successions or spatial diffusion using markov chains.

The attractiveness of Markov chain analysis is that the models parameters are easily estimated. The transition probabilities can be statistically estimated from a sample of transitions occurring during some time interval. The serial dependence which is the defining property of a Markov model is also potentially attractive for a more specifically geographical reason. It has been said that the first law of geography is that nearby things are more alike (Tobler, 1970). The basic structure of a Markov model avoids the necessity of replicating the analysis over as many spatial units as make up the study area, so that in generalizing the processes involved the technique provides overall insight which may not be so readily attainable with other approaches The detection of functional relationships between species and environment and the testing of ecological theory tend to be secondary considerations (Guisan & Zimmermann, 2000).

During the previous decades the conceptual and practical advantages have encouraged geographers to use Markov models to describe and predict changes in land use, population distribution, residential structure, transport networks and industrial structure and pattern. In the domain of land use planning, modeling of land use change as a Markov process has been attempted by a number of authors. Bourne (1976) utilized the Markov model to predict land use in the central city, and to aid in probing the questions of process stability and similarity.

Bell (1974) addressed the issues of dependence and process evaluation through the use of Markov model analysis. Robinson (1978) explored the utility of this model by addressing the issue of relationships between types of uses in terms of persistence and rigidity of land use environments. All of these studies showed that the model is capable of providing some answers, albeit tentative as they are too many questions concerning the land use change. The model has found a wide range of application in forest succession studies.

Leak (1970) simulated forest succession by explicitly modeling the birth and death of individual stems and then aggregating the stem-level outcomes to make stand-level predictions. Horn (1975 a, b) took this same individual stem approach, but modeled the inter temporal transitions of saplings into the canopy. His empirical work applied a model of synchronous replacement of individual canopy trees by individual understorey stems, but he examined analytically the stability of more complex Markov models of forest succession. Usher (1966) defines the states as diameter classes rather than species and projects volume changes over time. Usher and Parr (1977) applied this type of model to successional changes in Ghanan termite colonies. Binkley (1980) has tested the stationarity of the markov process in predicting the succession of hard wood forests in Connecticut.

Thorton &Jones (1978) has used these models for dynamic agricultural land use modelling with respect to cropping patterns. (Turner, 1987) used it for predicting the temporal changes in land use patterns in Piedmont County in Georgia. Petit *et* *al*.,(2000) use these models for quantifying processes of land cover change in south eastern Zambia. Muller and Middleton (1994)used markov model to make quantiative comparisons of land use changed dynamics in Niagara region. These models are relatively easy to apply to dynamics in highly complex vegetation, and have been used to study succession and obtain short-term quantitative predictions of land use and land cover changes(LULCC)(Balzter, 2000; Logofet & Lesnaya, 2000). They can also differentiate local from regional drivers of LULCC (Logofet & Lesnaya, 2000), which is crucial for informing public policies on resources conservation and adaptation to climate change. Markov chains have been used to model changes in vegetation types on a variety of spatial scales. Changes on small areas of less than a few hectares; (Austin & Belbin, 1981); or on a single small plot (Lough *et al.*, 1987).

Few studies have attempted to link satellite remote sensing and GIS to stochastic modelling methods in land cover change studies, despite the fact that the techniques for such linkages have become mature in recent years due to advances in the technology of GIS and its integration with remote sensing. In this research an attempt is made to combine satellite remote sensing, GIS, and markov modelling to analyze and predict land cover changes due to *Mimosa pigra* expansion in Lochinvar National Park of Zambia. The techniques of satellite remote sensing and GIS are integrated to quantify and analyze land cover changes using LANDSAT TM and ASTER data and field surveyed *in situ* data. Markovian modelling is then used to examine the stochastic nature land cover change data and to project the stability of future land development in the region. The integration of satellite remote sensing, GIS, and markov modelling provides a means of moving the emphasis of land cover change studies from patterns to processes.

1.6. Research Objectives

General Objectives

The objective of the study is to map the land cover changes in Lochinvar National Park of Zambia using multi-spectral, multi-sensor, multi-temporal datasets so as to understand the spatio-temporal proliferation of *Mimosa pigra* and to test if markov chain models can be used to predict the expectable invasion of the alien plant in future.

Specific Objectives

1) To detect and map *Mimosa pigra* invaded areas from time series satellite datasets (LANDSAT TM and ASTER) and relatively prioritize the areas for management activities.
2) To evaluate the changes in natural land cover as a result of *Mimosa pigra* invasion through area statistics derived from the generated land cover maps
3) To predict the expectable invasion zones of *Mimosa pigra* using first order markov chain

1.7. Research Questions

Related to objectives 1 and 2

- Which of the datasets available enables a better identification of mimosa growing areas?
- Which of the image classification methods is optimal for mimosa delineation?
- What is the optimal number of land cover classes to distinguish mimosa growing areas?
- What are the area statistics of each land cover classes identified earlier?
- What are the reasons of mimosa proliferation in the study area?
- What are the management priorities in Lochinvar National Park and what are the available options for controlling mimosa proliferation in the study area?

Related to objective 3

- What are the transition probabilities of one land cover class to change to the other over years?
- What is the overall transition probability of the various land cover classes of the region to a mimosa affected area?

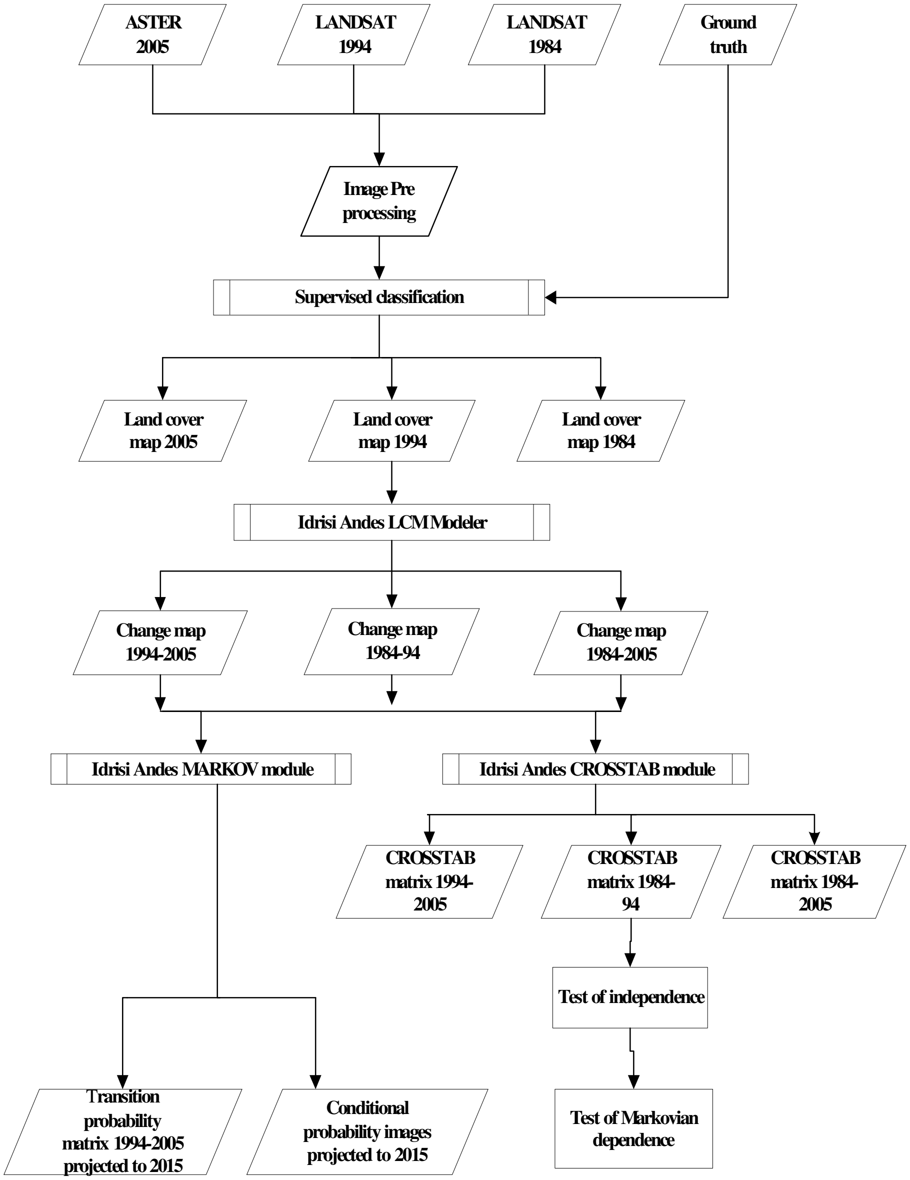


Figure1. 5-Conceptual Framework of Research

2. Study area

Lochinvar is a small National Park lying on the southern edge of the Kafue Flats in Zambia as shown in figure 2.1 , between 15^{0}43’ and 16^{0}01’S and 27^{0}10’and 27^{0}19’E. Formerly a cattle ranch, it was gazetted as a National Park in 1972. The Park covers an area of 410 sqkm, which stretches about 32 km from north to south and 13 km from east to west. Bounded on the north by the Kafue river the floodplain occupies about two-fifths of the total area and has an elevation between 975-981m above the sea level.

Figure2. 1 -Map showing the location of Lochinvar National Park, Zambia (Source- www.ngoko.com/safaris/maps/lvnp_big.gif)

2.1. Climate

The climate of Lochinvar National Park is marked by three distinct seasons 1)Cool dry season from (April) May to August 2) Hot dry season from September to October and 3) Wet warm season extending for 5 months from November to March The area receives an average annual rainfall of 800mm, much of it in December – February

The temperature of the area is generally warm ranging from 22^0C in June /July to 27.5^0C in October, the mean maximum and minimum ranging from 22^0C to 30^0C in October and 14^0C to 24^0C) in July respectively. The rate of evaporation, except in the peak rainfall months of January –March is higher than rainfall Potential evaporation is 1700-2200mm. This indicates that there are only three months of water surplus in the year, and, there is generally water deficit in 9 months of the year for plant growth.

2.2. Geology and Soils

The geology of the Kafue Flats represents one of the ancient landmasses of the African continent. It was formed over time through gentle tectonic forces, which led to a gradual uplift and subsidence, giving way to a gentle undulating landscape of "swells and depressions". A major fault divides the woodlands from the termitaria zone. Thick sediment overlies the grits, shales and sandstones of Karoo formation which occur in the termitaria and floodplain zones.

The soils of the Park area are originated as heavy, black, crack montmorillonitic clays , with lime concentrations in their lower layer, seasonally flooded, drying out to varying degrees and for various lengths of time (Ponnamperuma,1964). Rainfall has a profound effect on the soils of the Kafue Flats. Any differences between the layers appear to be as a result of differences in hydrological conditions between stands, modified by the extent to which sedimentation occurs and thus by the rate at which ferrolysis is progressing. The soils of the floodplain are mostly impermeable montmorillonitic cracking clays.

The termitaria zone is flat above the level of prolonged flooding where tree growth is restricted. The grey clay of the depression exhibit 'gilgai'microrelief which is lacking in the sandier clays of the higher ground, adjacent to seasonal streams and ancient drainage channels The top soil is strongly acidic at most places and is the lightest textured fraction of the profile. It contains high proportion of organic matter in bands of 2-8cm thick, the result of Lechwe trampling vegetation and faeces as the feed in shallow water .The topsoil is underlain by a compact white silty or sandy mottled layer between 2- 8 cm thick. This layer overlies the alkaline subsoil containing lime nodules at varying depths. Despite the strong acidity of the top soil in most of the study area the soil apparently contains adequate amounts of calcium, magnesium and potassium to support plant growth. .Mechanical and chemical analyses of soil samples gave no indication of soil physical or chemical differences that might be associated with differences in vegetation between the stands (Douthwaite & van Lavieren, 1977).

2.3. Topography and Hydrology

The Kafue flats relief is generally plain with gently sloping gradient towards where the floodplain is situated which is about 975m to 981m above sea level, the water from the runoff and the Kafue River channels inundate the floodplain and swampy areas each year. The water table remains high during the dry season.

Lochinvar National Park is flooded by water from three sources –local rainfall, tributary streams and the Kafue River. The three types of flooding come at different times of the year and have different characteristics. Flooding from rainfall can occur during the peak of the rainy season and such floods are quite shallow. Tributary and streams flood during rainy season and since these streams do not have channels the water spreads out over the surface of the ground. The greatest source of floodwaters is Kafue river itself. These waters come from the upper Kafue basin and because of the distance this water must travel, the flood crest is not reached until the after the rains have ended. Flooding occurs because of low gradient and water flows from the river to the Chunga lagoon and this is spilled to the floodplains of Lochinvar. No data is available on the exact extent and area of flooding however it is known to go beyond the termitaria zone. The great variation in the height of flood from year to year is caused primarily by variation in the run off from the upper basin The floods normally begin to rise with the onset of the rains in mid October .peak flood levels usually occur at the end of April, about a month after the end of rains. The floods begin to recede during the dry season from late June and reach their lowest by November.

After the construction of the Ithezi-tezhi dam and the Kafue Gorge dam there has been a change in the natural flooding regime affecting the extent, time and duration of floods and changing the vegetation of the area. This have had serious consequences on grazing and migratory patterns of lechwe, fish and avi fauna ecology and growth of invasive aliens

2.4. Socio economic values

Lochinvar National Park was designated as a Ramsar site in 1991 owing to its exceptional avian diversity and ideal habitat to the semi aquatic endemic antelope Kafue lechwe,- *Kobus leche kafuensis* Almost 40,000 lechwe in the South Bank of the Kafue flats is found on Lochinvar.alone The Park is also known for large mammals and insect diversity . The Chunga lagoon also supports large fish population which sustains the livelihood of fishermen living adjacent to the park.

2.5. Wetland Vegetation

The vegetation of the park is of three main types 1) Floodplain 2) Termitaria and 3) the Woodlands.

The floodplain, with very little local relief, lying at the lowest elevations is subject to seasonal inundations. Because of the low gradients and the generally impervious nature of the soil, local rainfall, cause flooding beginning in November and December. Run-off due to local rainfall in the Park area supplies more moisture to raise the water level and flooding of an ever greater area continues through January to March .With normal rainy conditions the waters will slowly cover the flats and by the end of the rainy season and in March and April the area is submerged. Many of the aquatic and semi-aquatic plants grow well under these circumstances. In this area the most dominant plant species found are *Nymphaea* (waterlilies), *Vossia cuspidata* (hippo grass) , *Echinochloa stagnina* (water grass), *Oryza longistaminata* (wild rice) , *Phragmites spp*, *Acroceras macrum, Leersia denudata, Sacciolepis africana , Paspalidium platyrrhachis and Vetiveria nigrtana* .In other areas *Polygonum senegalnese, Typha domingensis and Nymphoides spp* may form the most conspicuous elements of the vegetation (Douthwaite & van Lavieren, 1977) . There are also a variety of herbs found in the area the most common ones being *Ambrosia maritima, Hibiscus trionum, Heliotropium baclei and Nidorella auriculata*.

Above the high water level of the river flood is land which, because of the flatness of the terrain and poor drainage conditions becomes water logged during rainy season due to local rains and run off .But this area is not subject to prolonged flooding from the Kafue River. These conditions are inimical to tree growth ,nonetheless termites are active here and are responsible for raising the great mounds which form the conspicuous part of the landscape .As a result, this treeless zone has been called the "Termitaria zone (Douthwaite & van Lavieren, 1977). During the rainy season its an area of dense grass growth .On termitaria in sandy soil, the most common species found are *Euphorbia candelabrum, Azanza garckeana, Adansonia digitata* and *Hyphaene ventricosa*. Mounds in the clayey soil are commonly covered by *Diospyros mespiliformis, Albizia harveyi, Lonhocarpus capassa and Commiphora edulis*. Woody plants may grow on some of the large, older termitaria, giving rise to the other name of this area; the bush group grasslands (van Rensburg, 1968a).

The remainder of the park is at such an elevation and under such conditions, that drainage is better and tree growth is not suppressed to any great extent. The termites are active too and large mounds are found amongst trees. In general the trees are well spaced and grass growth beneath producing the savannah. Locally this type of vegetation is referred to as "Munga woodland "because of the presence of the thorny trees, primarily species of Acacia (Fanshawe, 1969). Some of the common species found here are *Acacia nigrescens, Acacia abysinica, Acacia tortolis, Acacia nilotica, Acacia xanthophloea, Combretum collinum, Pericopsis angolensis, Terminalia sericea, Dalbergia melanoxylon, Acacia polycantha, Acacia sieberana , Albizia harveyi etc.*

In some areas Mopane woodland is also found where the predominant tree is *Colophospermum mopane.* The commonly found trees in this area are*, Adansonia digitata (* Baobab tree), *Commiphora mollis* and *Euphorbia candelabrum..*

Studies conducted by Rees (1978 a)reveals the fact that differences from vegetation between different units are attributable mainly due to hydrological differences (depth and duration of flooding and length of dry period) rather than to intrinsic physical or chemical properties of the soil

3. Materials and Methods

3.1. Materials

Images	
LANDSAT 1984 (Dry season)	**Acquisition date-05-09-84** **Product – NLAPS-** Radiometrically and geometrically corrected
LANDSAT 1994 (Dry season)	**Acquisition date - 04- 09-94 –** **Product –NLAPS-** Radiometrically and geometrically corrected
ASTER 2005(Dry season)	**Acquisition date – 13-06-05** **Product- Level 1 B** Radiometrically calibrated and geometrically co-registered
Software	
ERDAS Imagine version 8.7	
Arc GIS version 9.1	
Idrisi 15- Andes Edition	

Table3. 1- Table showing the materials available for study

3.2. Pre field work phase

Pre field work phase is a preliminary but an important and fundamental step before undertaking a field survey. During this stage all the available information about the study area was collected, compiled and rectified. The following steps had been carried out before the fieldwork.

3.2.1. Image pre processing

In this study multi temporal images were used from different sensors. In order to compare separate images pixel by pixel, the pixel grids of each image should conform to the other images in the database. Hence pre-processing techniques like georeferencing, image to image registration and reprojection of the images were performed on the datasets.

The topographic sheet of Lochinvar National Park was reprojected to the local Zambian coordinate system the specifications as shown in table 3.2

Projection	Transverse Mercator
Spheroid	Clarke 1880
Datum	Arc 1950(Zambia)
Scale factor	0.9996
Longitude of central meridian	27^0E
Latitude of origin of projection	0^0N
False easting	500000 m
False northing	10000000 m

Table 3. 2- Specifications of the Zambian coordinate system used for reprojection of the images

The next step was to georeference the images .Georeferencing is the process of assigning map coordinates to an image data. The images of both LANDSAT and ASTER obtained from the data processing centre were already projected to a desired plane and referenced to UTM coordinate system. Georeferencing of the ASTER images were done by stacking only the VNIR and the SWIR bands where the ground control points were imported and the image was reprojected to the required local coordinate system. The LANDSAT TM imagery of 1984 was georeferenced to ASTER imagery using image to image co-registration method in ERDAS Imagine. Similarly image to image co registration was also done for LANDSAT 1994 to ASTER imagery in order to make it conform to the other images. All the images were resampled using, first order transformation, and nearest resampling method of the uncorrected imagery was performed. The total Root Mean Square (RMS) error for LANDSAT images was found to be 5m for 1994 and 10 m for 1984 images. For ASTER imagery the RMS error was found to be 3 m. The RMS error represents the degree of correspondence between the calibrated fiducial mark coordinates and their respective measured image coordinate values. Large RMS errors indicate poor correspondence (Erdas, 2003).

Both the LANDSAT and ASTER image scenes were subsetted in order to limit the size of the study area to Lochinvar National Park. For the purpose of field work and visual classification hard copy colour composite images were made for the data of ASTER 2005, wet season using band combination 3,4,2 in RGB combination for improved vegetation discrimination.

Unsupervised classification was performed on the most recent ASTER wet season imagery. Accordingly classification was done with 7 classes which were identified as water, submerged vegetation, woodlands, grassland type 1, grassland type 2, grassland type 3 and open mimosa.

3.3. Sampling design

Stratified random cluster sampling was used to generate the primary cover data**.** Each land cover class derived from the unsupervised classification was considered as a stratum. Random numbers were generated and imported as points in ERDAS Imagine. Allocation of these points to each of these strata was based according to the area proportions. Subsequently a cluster of two points were generated around each random point at a distance of 200m in the north and south direction. A total of 102 sample plots were generated. However during field work it was impossible to visit all the samples plots due to inaccessibility of the area.

3.4. Data collection

Field work was carried out from September 23 to October 21, 2006; the main objective was to collect data required for training and validation for classification of the ASTER 2005 imagery. The sampling sheet (as shown in appendix 1) used for primary data collection recorded observations such as vegetation cover; presence or absence of mimosa, average height, and crown cover %. The coordinates of the sample plots were located with help of the GPS, topographic map and the ASTER colour composite imagery. Quadrants of 20 X 20m were taken and line intercept transect method was used to record the above observations The measuring tape was held in such a manner that it passes through the centre point of the plot and observations could be taken along 20 m in north- south and 20 m in the east-west direction within the quadrant . Observations were recorded at every 50 cm interval for the presence or absence of mimosa. Care was taken during data recording that only if mimosa crosses or intercepts the vertical plane made by the line segment its presence was recorded

In most of the areas *Mimosa pigra* was found growing in varying densities mixed with the grasslands. Certain sample plots were inaccessible due to heavy infestation by dense impenetrable thickets of mimosa. Several GPS coordinates were recorded in such areas and also in newly infested locations. In total 156 field observation points were utilised for performing supervised classification of the ASTER imagery as shown in appendix 2**.** Secondary data were also collected like topographic maps, meteorological data, and vegetation data of Lochinvar before and after the construction of the Ithezi-tezhi dam and Management plans. Interviews were conducted with the Park management staff and with the local people in a village called Nymba which is a settlement situated on the eastern side adjacent to the park.

3.5. Post field work phase

3.5.1. Image analysis

During the post fieldwork phase supervised classification was performed on the wet season ASTER imagery by utilising observation points recorded during field visit. The image was again subsetted as shown in figure 3.1 below since it was known that mimosa was not found beyond the termitaria zone.

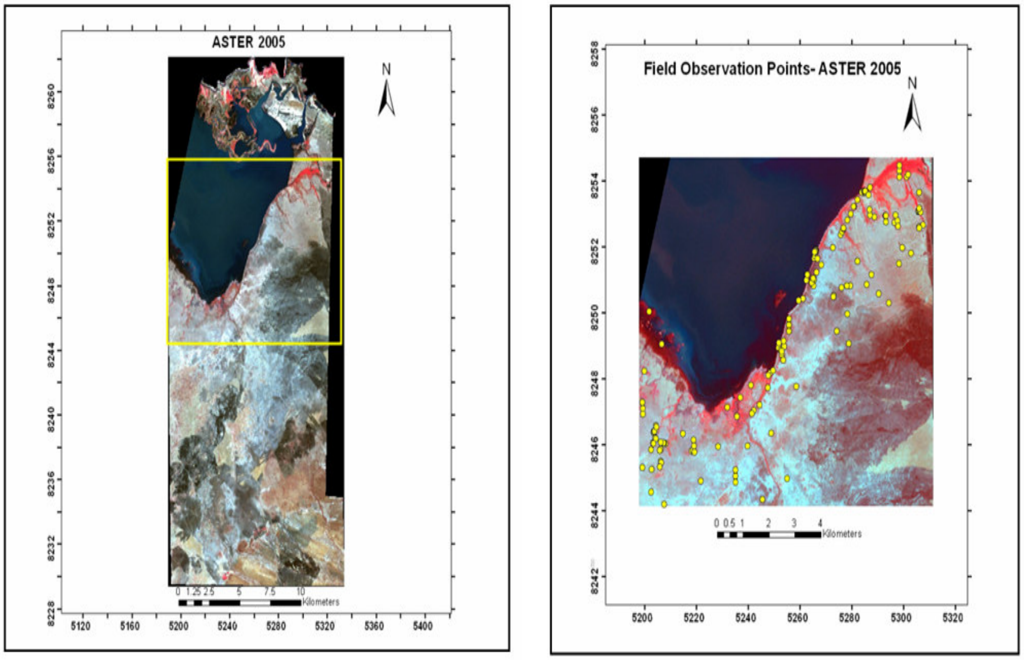


Figure 3. 1- Map showing the area subsetted for the study purpose and the field observation points recorded

It was found that there was considerable spectral confusion between mimosa and certain types of grasslands. Hence supervised classification was also carried out on dry season imagery of ASTER 2005. This was because during data collection it was observed that during dry season certain species of grasses near to the fringes of the lagoon remained green but those found towards the inland were dry. Whereas most of the *Mimosa pigra* near to the lagoon and towards the inland remained green and those that were dry was completely devoid of leaves and had a characteristic brown colour which makes it easy to distinguish from all other vegetation.

It was found that though the classification results were better compared to wet season imagery the classifier was unable to distinguish mimosa from grasslands especially in those areas where mimosa was mixed with grasslands. Though several attempts of supervised classification were made to improve the classification result, it was difficult to identify and separate mimosa infested areas from pure grasslands especially towards the lagoon. All the three types of supervised classification like Maximum likelihood, Minimum distance and Mahalanobis were carried out without significant improvement in the results. The overall accuracy was found to be 64%, 60% and 52%. The accuracy for class mimosa was 55%, 58% and 50%.

Attempts were made to improve the classification results by generating the textural properties of the various vegetation cover. Texture is the frequency of tonal change in an image. It determines the overall visual smoothness or coarseness of the image features. An interpreter can often distinguish the between features with similar reflectances based on their texture differences (Lillesand & Keifer, 1979). Much information is contained in the relationship between adjacent pixels, including texture and shape information, which allows for identification of individual objects as opposed to single pixels (Thomas *et al.*, 2003). Such an object-oriented approach allows the user to apply locally different strategies for analysis. The use of texture in addition to spectral features for image classification might be expected to result in some level of accuracy improvement, depending on the spatial resolution of the sensor and the size of the homogenous area being classified (Mather, 1998). The objective for texture classification is to extract the intrinsic features for textures in a few parameters and then design a classifier to use these parameters as features to classify the textures (Campbell, 2002).

The textural properties extracted were mean, variance, homogeneity, contrast, dissimilarity; entropy, second moment, and correlation were generated using ENVI. Several attempts were made to classify the images based on these properties and their combinations; there was no considerable improvement in the results. Though it was possible to identify some new patches of mimosa infested areas most of the areas still remained unidentified. This is because if the spatial resolution of the image is fine relative to the scale of tonal variation, texture can be a valuable source of discriminating information. Conversely where the homogenous regions in the image are small it may prove difficult to estimate texture, for texture is a property of an area rather than a point. Moreover the area over which texture is measured contains two or more different regions or categories then the texture measures may not prove to be useful (Mather, 1998). The area occupied by dense mimosa (areas more homogeneous) is small, the only two patches found along the Nampongwe stream on the western side and Mainda channel on the eastern side (figure3.1). Thus attempts to classify based on pure textural measures were not successful.

NDVI is one of the most widely used vegetation indexes and its utility in satellite assessment and monitoring of global vegetation cover has been well demonstrated over the past two decades (Leprieur *et al.*, 2000). NDVI has more advantages in representing surface vegetation coverage and revealing vegetation green. It also can quantitatively or qualitatively represent vegetation activity, and it is more sensitive to detect green vegetation by single band (Zhang *et al.*, 2003). NDVI was calculated for the whole image.First the at sensor radiances were converted to radiances and then the radiances were converted to reflectances. The standard equations of ASTER and LANDSAT were used for conversion purposes.

It was noticed that during dry season there was considerable burning in the eastern side of the park. The extent of burned area was different in all the three images. It was found that among them ASTER had the most extensive burned area. Moreover since ASTER 2005 imagery was used for field work the extent of burned area was known. Hence it was decided to digitize the burned area, mask it and assign it a separate class called burned areas. This mask was also applied to the to the other images because if an area is burned in one year there cannot be any land cover change detected for that area in the next image. During field work sampling points were assigned to this area it was seen that there was no mimosa found here and these areas comprised of only burned grasslands and shrubs.

3.5.2. Supervised classification

Maximum Likelihood classification was performed in ASTER 2005 dry season imagery. This technique was chosen because it uses the mean values and covariance matrix of the classes to assign each pixel to the class with the highest probability thus, gives a reliable result (Lillesand & Keifer, 1979). It assumes that the statistics for each band are normally distributed. As mentioned earlier this imagery comprised of stacked layers of NDVI, VNIR and SWIR and textural properties. Similarly for 1984 and 1994 images classification was carried out based on signatures extracted through visual interpretation and vegetation maps.

Since in 1984 and 1994 images, certain classes like dense mimosa and shrubs could not be detected, a single pixel was assigned representing each of these classes to the burned area. By doing this Idrisi Andes calculates the change in the area statistics experienced by each of the cover classes in the multitemporal series. So if a particular class is completely absent and remains unrepresented in any one of the land cover images it would not be possible to determine how many pixels have changed for that particular class from the previous to the next land cover image. Thus single pixels representing dense mimosa and shrubs classes were assigned for both the LANDSAT images on exactly the same geographic coordinates using the modeler function in ERDAS. All the three images were recoded and given exactly the same class names and numbers. The various classes that could be distinguished were.

Class 1 - Water or WAT –This class represents the water body mainly the Chunga lagoon and the streams
Class 2 - Grasslands or GRA- This class represents the areas with pure grasslands that are not mixed with mimosa
Class 3 - Open mimosa or MIMGRA- This class represents the areas where mimosa is found in varying densities and extents mixed with grasslands. Mimosa in this area can be either found as thick patches of few plants, or sparsely populated or thinly populated with few plants. These areas have been previously occupied by pure grasslands but now have mimosa invading into it.
Class 4 - Burned areas or BURN – These areas represents the grasslands which are burned every year during dry season by the local people.
Class 5 - Shrubs or SHR – This class represents the other encroachers like Acacia sps, *Dichrostachys cinerairia* etc.
Class 6 - Dense mimosa or MIM- This class represents the areas with very dense impenetrable thickets of mimosa.

Accuracy assessment was carried out for ASTER imagery using 43 validation points that were collected during the fieldwork. The overall accuracy, producer and users accuracy was calculated using confusion matrix. Kappa statistics was also calculated to have an idea of magnitude of chance agreements in classification.

3.6. Change detection

3.6.1. Land Change Modeler

Land Change Modeler for ecological sustainability is an integrated software environment developed by Idrisi 15 Andes version for analysing land cover change given there are two land cover maps have identical legends (same code for each class). The change analysis panel provides a rapid quantitative assessment of change by graphing gains and losses by land cover categories. A second option, net change, shows the result of taking the earlier land cover areas, adding the gains and then subtracting the losses. The third option is to examine the contributions to changes experienced by single land cover (Idrisi, 2006). The Change analysis was performed between pairs of images 1984 -94, 94-2005 and 84-2005. Accordingly the transitions and exchanges that took place between the various classes during the years were obtained both in a map and graphical form. All the units were changed to hectares. Transitions below 0.1 ha were ignored.

Cross classification find its most common application in land cover change analysis where a cross tabulation or a cross correlation is done between two qualitative maps of two different dates that targets on the same features (Idrisi, 2005). It is used to compare two classified images where the classification assigns the same unique and distinct identifier to each class on both the dates. The aim is to evaluate the whether areas fall into the same class on the two dates or whether a change to a new class has occurred. In Andes edition by running a CROSSTAB module we get a new image based on all the unique combination of values from the two images in which each unique combination of input values has a unique output value and a cross tabulation table. The cross tabulation matrix that shows the distribution of image cells between the classes. The categories of date 1 are displayed on the X axis while in Y-axis displays the same categories at date 2. The cross tabulation shows the frequencies with which classes have remained the same (those along the diagonal) or have changed (off –diagonal frequencies). Cross correlation images show all possible combinations that can be used to produce two types of change images. These relative frequencies are known as transition probabilities and are an underlying basis for Markov Chain prediction of future transitions.

3.7. Markov Chain Model

In this study using the classified multitemporal images, a Markov module was performed in Idrisi Andes to predict the changes of the land cover in the study area in the future. The following output was obtained:

1) A transition probability matrix – This is automatically displayed and it expresses the likelihood that a pixel of a given class will change to any other class (or stay the same) in the next time period.
2) A transition area matrix – This expresses the total area (in ha) expected to change in the next time period
3) A set of conditional probability images – one for each land cover class. These maps express the probability that each pixel will belong to the designated class in the

next time period. They are called conditional probability maps since this probability is conditional on their current state.

The results from the cross classification proved that there has been aggregate changes in proportions of land cover over the period from 1984-2005 but whether or not this can be attributed to a Markov process is what the analysis will attempt to determine. The reasonable way to proceed is to test first for independence against the alternatives and to then test for first order markovian dependence (Bell, 1974). The only other inference that can be done with data from three points involves a test of stationarity of the transition probabilities, once the first order Markov model has been accepted (Bell, 1974).

The demonstration of stationarity while crucial to the use of this technique goes beyond the scope of this research since it involves lot of mathematical computations. At first the output results from the cross classification of 1984 -94 images were used to test for the hypothesis of independence. The testing of statistical independence involves a procedure for comparing the expected numbers under the hypothesis to the actual numbers (Weng, 2002). If the number of land cover categories is M, then the statistic to be computed is Karl Pearsons χ^2 with $(M-1)^2$ degrees of freedom. This statistic was called K^2 to differentiate it from its distribution (χ^2). If N_{ijk} stands for the number of cells having first use category i and subsequent uses j and k in later time periods we define $N_{..k}$ as the number of cells in use k at the last time (2005). $N_{.j.}$ as the number in use j at the previous time (1994), and $N_{i.}$ as the number in use i at the earliest time (1984). Under the hypothesis of independence the proportion of the total number of cells N in use succession (i, j, k) is the product of proportions ;($N_{i..}$ / N) x ($N_{.j.}$/N) x ($N_{...k}$/N) and the expected number is this product times the total number of cells N. If we call the expected numbers $\mathbf{N_{ijk}}$ and the observed numbers N_{ijk} .Then the statistic to be computed is

$$\mathbf{K^2}=\Sigma_i\Sigma_j\Sigma_k(N_{ijk}-\mathbf{N_{ijk}})^2/\mathbf{N_{ijk}} \ldots\ldots\ldots \text{eqn } \mathbf{6}$$

The 0.05 critical region for M=6 is thus any value of K^2 greater than 179.6**.** Any computed value of less than this critical number will lead to conclusion that the data are compatible with hypothesis of independence. This test of independence was also done for the land cover maps between 1994 -2005 using the same formula but replacing i and j with j and k respectively. Accordingly it was proved that the computed value was greater than this critical number hence the hypothesis of independence was rejected which means that the two land cover maps are highly dependent.

The alternative to independence is dependence of any sort, including markov chain as but one of many alternatives. A reasonable way to proceed is to, is to test for the first order Markovian dependence (Bell, 1974). In order to establish the validity of Markovian property, it is necessary to use a chi square goodness-of-fit test. The observed data for use in computation of the test statistic are the number of hectare cells that changed during 1984 -2005 which can be obtained from the cross tabulation of 1984-2005 image. According to the Markovian hypothesis the expected number can be obtained by the following procedure. If the process is markovian the transition probability matrix governing the period 1984-2005 can be obtained by multiplying the 1984-94 and 1994-2005 matrices which is a direct application of Chapman – Kolmogorov equation (Stewart, 1994). These transition probabilities are used in the following formula to compute the expected numbers

$\mathbf{N_{ijk}}=\Sigma_j\,(N_{ij.}\ )(N_{.jk})/N_{.j}$ .... eqn **7**

Where:

$N_{ij.}$ is the number of transitions from category i to j during the period 1984 to 1994

$N_{.jk}$ is the number of transitions from category j to k during the period 1994 to 2005; and

$N_{.j.}$ is the number of hectares cells in category j in 1994

If N_{ijk} stand for the number of cells having a category i in 1984 j in1994and k in 2005, and $\mathbf{N_{ijk}}$ for the expected number then K^2 can be computed for goodness of fit of the Markov hypothesis.

As mentioned earlier the test for stationarity was not performed since it's beyond the scope of the study. However it was proved after computation from the above results that the process is not stationary. The stationarity assumption means that the changes recorded from the 1984-94 and 1994-2005 result from the same transition mechanism.

3.7.1. Test of independence

Having multitemporal data for three years at first the hypothesis of independence has to be tested. According to the Markov process the land cover of any cell chosen at random should be statistically dependent only on the preceding year (Bell, 1974).Hence a reasonable way to proceed is to first prove whether the land cover images for two years are statistically dependent or not. If they are dependent then the next step would be to test if the process of change is markovian or not**.** Here the null hypothesis is that the land cover images are independent and the alternative hypothesis is that they are dependent. On performing the test it was proved that the two land cover images are highly dependent.

3.7.2. Test of Markovian dependence

Since it has been proved that the given two land cover images are highly significant, the next step is to determine whether this can be attributed to markovian process or not . Here the null hypothesis was that there was markovian dependence between the two land cover images and the alternative hypothesis is that there is no markovian dependence between the two land cover images. Using the formula given in section 3.7,the chi square test was performed

4. Results

4.1. Superivsed classification of images

Maximum likelihood classification was carried out on the subsetted images of ASTER 2005 and LANDSAT 1994 and 1984 .The result obtained is shown in figure 4.1, 4.2 and 4.3 respectively.

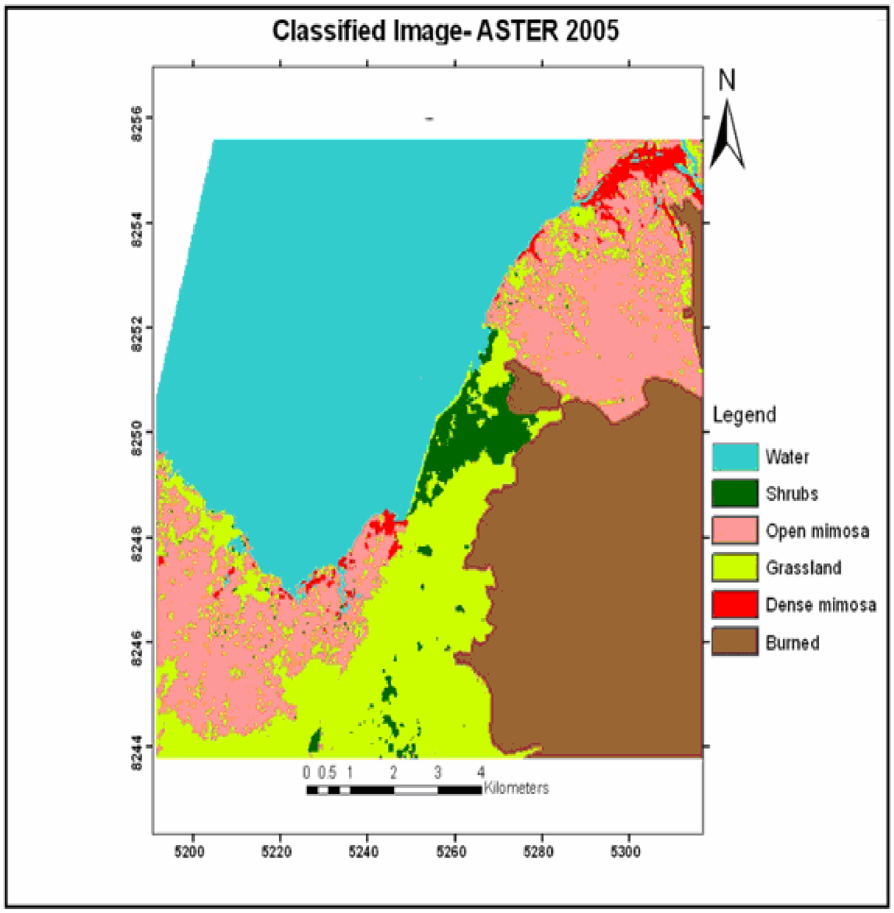


Figure 4. 1- Supervised classification of ASTER 2005

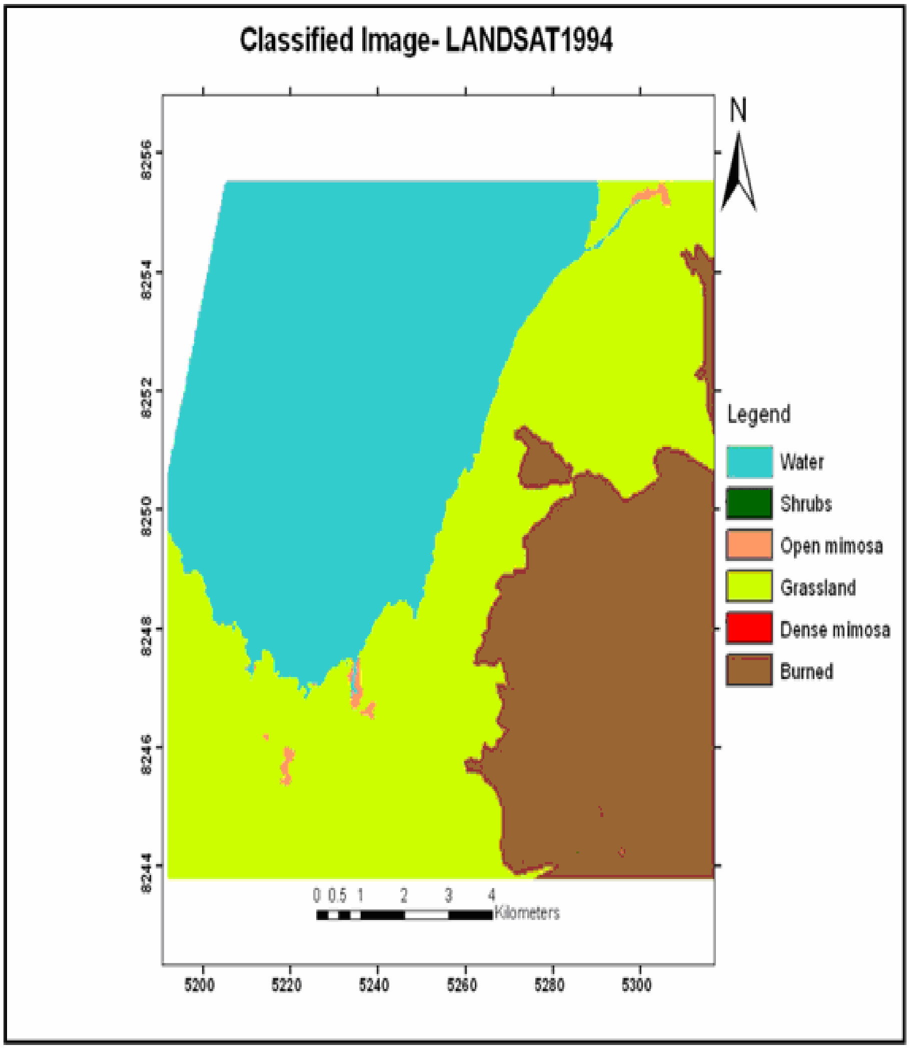


Figure 4. 2- Supervised classification of LANDSAT 1994

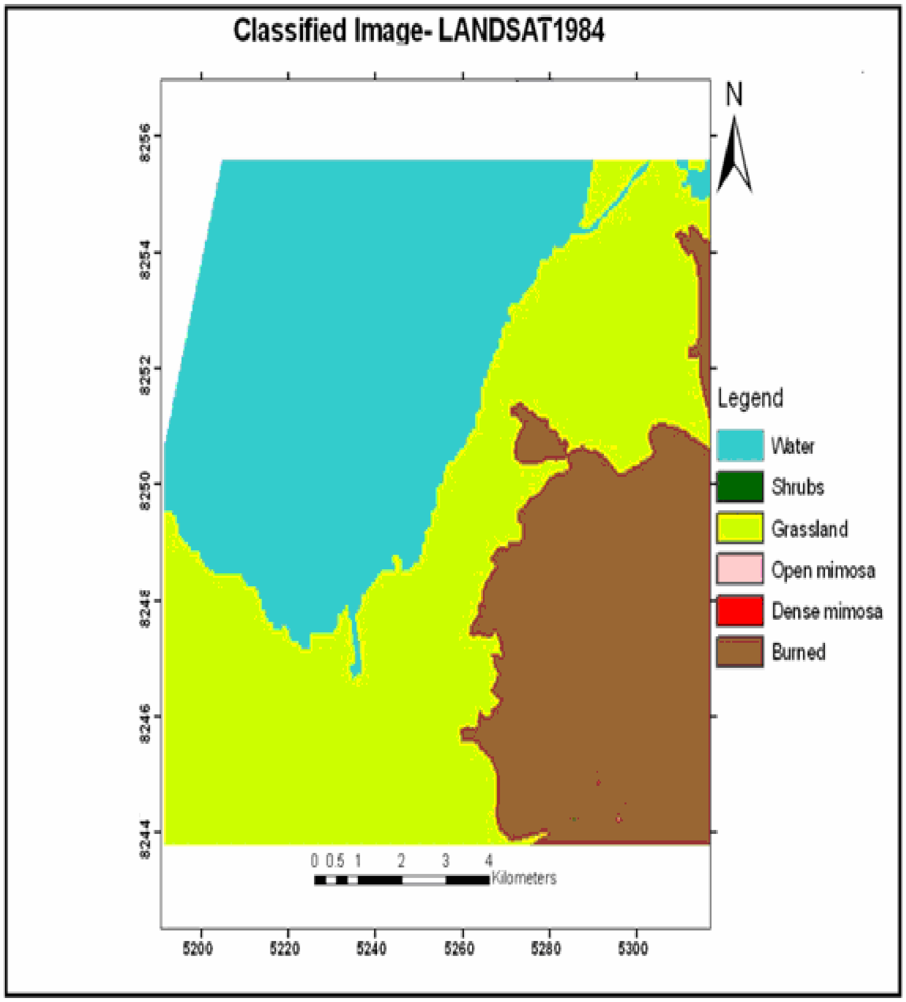


Figure 4. 3- Supervised classification of LANDSAT 1984

On comparing the results from 1984-94 it is evident that in 1984 the area surrounding the Chunga lagoon was completely covered by grasslands and not even a single patch of mimosa could be detected. After 10 years in 1994 as shown in figure 4.2 mimosa shows signs of expanding along the Nampongwe delta and the Mainda channel where it is found to be growing with grass. It was during the last decade, in 2005, *Mimosa pigra* has shown up as an invasive species covering almost the whole area surrounding the Chunga lagoon. This can be clearly observed on comparing the classified images of 1994 and 2005 where there seems to be an explosion of mimosa infestation on the western and eastern sides of the study area thus reducing the grasslands to a considerable extent. It can be noticed in 2005 image that it was even possible to identify two different densities of mimosa which are classified as dense mimosa and open mimosa as shown in figure 4.1. During this span of 10 years there has been some dynamic change in the environmental or flooding conditions that has contributed to this rapid spread. It can be clearly noticed from the multitemporal series of images from 1984 to 2005 that the area under grasslands has been drastically reduced.

It is also interesting to note that in 2005 there are clear signs of shrubs spreading the area and the spread seems to be coming from the inlands towards the lagoon. The concentration of shrubs in the area seems to be so dense (between the two big mimosa patches on the eastern and the western sides) as shown in figure 4.1 that not even a single patch of mimosa is found in between them and very little grasslands appear. Some isolated patches of shrubs are also found on the further end on the southern part of the study area between the pure grasslands and also in the eastern side of the study area where mimosa is found.

From the classified imagery it is evident that the growth of mimosa has started along delta and streams as shown in figure 4.1 and is spreading only along those areas where water is available. Hence large concentrations of mimosa grow extensively on the flat floodplains in all directions depending on the accessibility to water. It apparently seems from 2005 imagery that dense concentrations of mimosa are found mostly on the eastern side of the park surrounding the Mainda channel than on the western side where mimosa was first detected. Another interesting point that can be noticed is that though mimosa is found in areas where water is easily available it cannot be seen in the immediate vicinity along the fringes of the lagoon. This trend can be observed particularly on the western side of the park where it is possible to find some patches of pure grass on fringes of the lagoon after mimosa thickets.

4.1.1. Accuracy assessment

Classes	**Water**	**Grassland**	**Open Mimosa**	**Shrubs**	**Dense mimosa**	**Total**	**Error Of Commission**	**Users Accuracy (%)**
Water	8	1	0	1	0	**10**	**20**	**80**
Grassland	1	6	2	0	0	**9**	**33**	**67**
Open Mimosa	0	1	7	0	2	**10**	**30**	**70**
Shrub	0	1	0	5	0	**6**	**16**	**84**
Dense mimosa	1	1	0	0	6	**8**	**25**	**75**
Total	**10**	**10**	**9**	**5**	**8**			
Error of Omission	**20**	**40**	**22**	**90**	**25**			
Producers accuracy	**80**	**60**	**78**	**100**	**75**			
Overall accuracy	**74.4%**							

Table4. 1- Accuracy assessment of ASTER 2005

The accuracy assessment of ASTER 2005 image was done using 43 validation points that were collected during the field work. For the classes of interest, open mimosa, dense mimosa and grasslands a user accuracy of 70%, 75% and 67% was obtained respectively. As seen in the above table the lowest accuracy was recorded for grasslands and this was expected since there during signature recognition feature space revealed the confusion between grass and open mimosa grass. The overall classification accuracy was 74.4% and the overall kappa statistics was 0.70

4.2. Change detection using LCM

Land Change Modeler (LCM) was used to analyse the land cover changes between various classes from 1984 - 1994, 1994 - 2005 and 1984 -2005. The results of LCM model from 1984 to 1994 are shown below. The overall change in experienced by various cover classes has been shown in fig 4.4. It can be seen that the classes which apparently experienced gain in terms of area (ha) are water, grasslands and open mimosa.

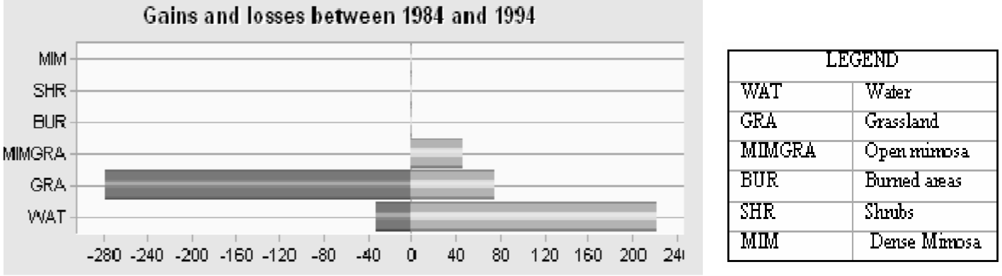


Figure 4. 4- Graph which shows the overall gain and loss of different cover classes in ha from 1984-1994

The burned areas are not taken into consideration since results cannot be analysed. However it can be also noticed that though grasslands have gained a few hectares experiences more loss than gain. This is evident by calculating the net gain or loss (in ha) for each cover class as shown in figure 4.5 shown below

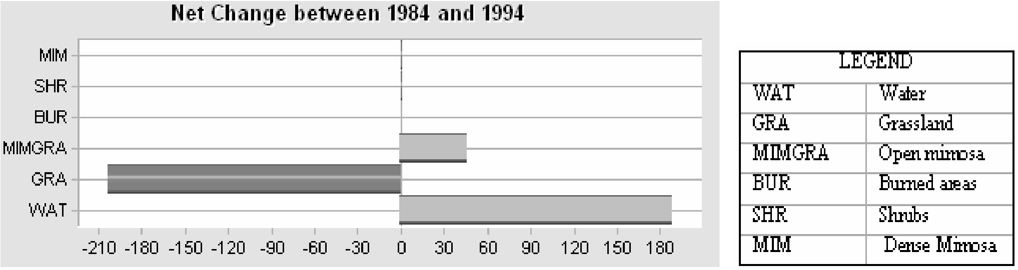


Figure 4. 5- Graph showing the net change experienced by different cover classes in ha from 1984 -1994

In this figure we find that there has been an overall reduction in grasslands but the area under the cover classes water and open mimosa has increased. These two classes have gained at the expense of grasslands which can be further proved by figures 4.6 and 4.7 as shown below. As mentioned earlier the extent of area under water keeps on varying depending upon the rains and the extent of flooding. This is relevant to the purpose of study because it is interesting to observe if mimosa shows preferential spreading towards the lagoon compared to the inland and whether this has contributed to the change in the size of the lagoon over the years. This is in turn would affect the availability of water for wildlife. It is quite clear from the figures that the only cover class that has contributed to the transition to mimosa was grassland as shown in figure below 4.7

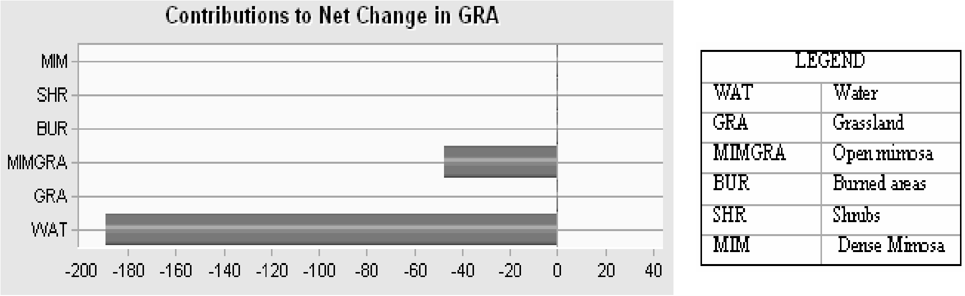


Figure 4. 6– Graph showing the land cover classes contributing to net loss of grassland from 1984 -1994

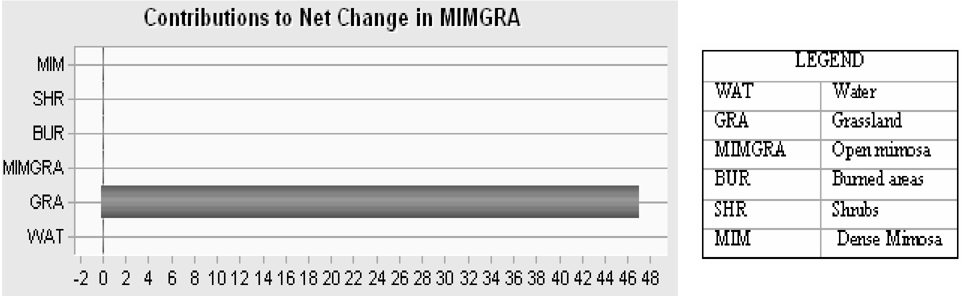


Figure 4. 7- Graph showing the land cover class that has contributed to expansion of open mimosa from 1984-1994.

Figures 4.8 is a Boolean map showing those parts of the study area that has experienced net gain and loss of grasslands during the decade. Figure 4.9 shows the beginning of infestation by *Mimosa pigra* in the study area. The results prove that during this decade grassland on the whole experienced more loss than gain.

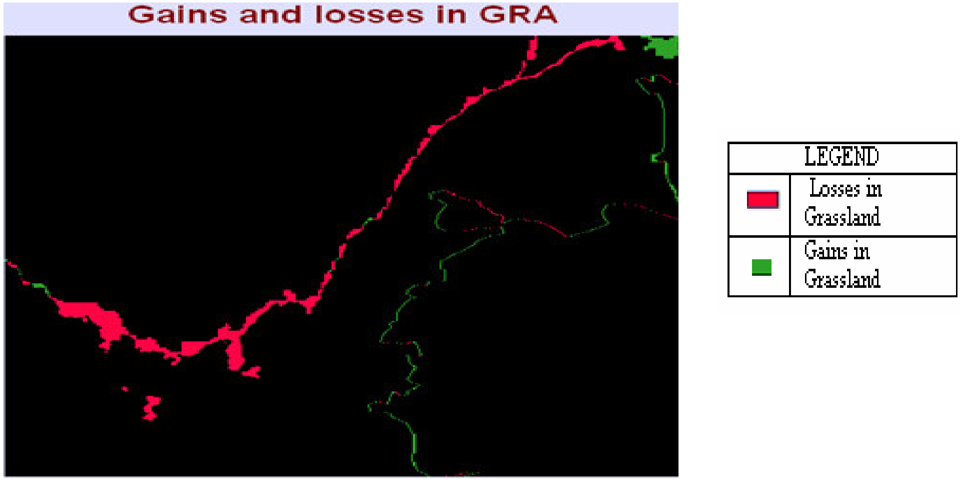
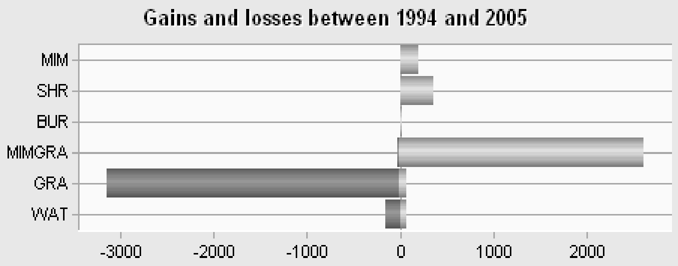


Figure 4. 8–Boolean map showing those parts of the study area where grasslands have experienced an overall gain and loss from 1984-1994.

Figure 4. 9- Boolean map showing the exchanges between the cover classes grasslands and open mimosa during a period from 1984-1994

LCM MODEL FROM 1994 -2005

The overall changes in the various cover classes experienced during this decade are shown in the figure 4.10. It can be seen that the classes which have significantly increased in terms of area are open mimosa, shrubs and dense mimosa.



LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure 4. 10– Graph showing the overall gains in different cover classes in ha during a period from 1994- 2005

It is evident from the figure 4.11 that during this period the area under grasslands has been subjected to tremendous pressure through spread of shrubs and invasion by mimosa. The rate of invasion by mimosa seems to be much higher than from the previous decade from 1984-94. Figure 4.12 proves that the cover classes that has contributed the most to the transition to mimosa is grasslands followed by water. The results of the classified image of 2005 (figure 4.1, pg 37) and figure 4.10 (above) shows that it was even possible to identify a new class representing dense thickets of mimosa.

Figure 4.13 show that the cover classes grasslands, water and open mimosa have undergone transition for the formation of the class dense mimosa. This is found to be interesting because taking into account the multitemporal sequence of images and the pattern of mimosa growth over the years it was assumed that the conversion to dense mimosa would be from those areas which were previously classified as open mimosa in the previous decade. But the results shows that during this decade there was an explosion in the growth of mimosa, that those areas which were not even classified under open mimosa in the previous decade has been converted to dense thickets of mimosa. This abrupt change indicates that there has been some factor within the invaded grasslands and the invader *Mimosa pigra* that has led to the rapid infestation of the area.

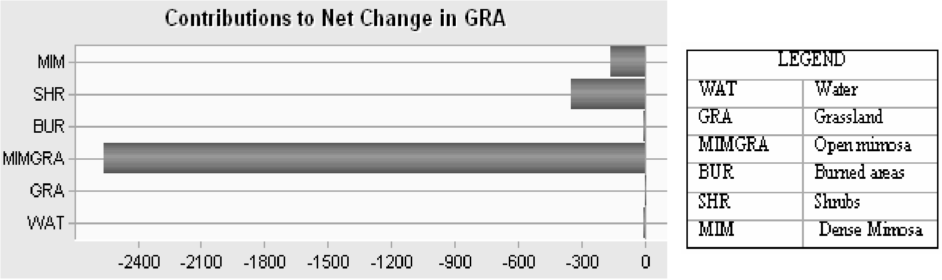


Figure 4. 11- Graph showing those cover classes that has contributed to net loss of grassland during a period from 1994 – 2005

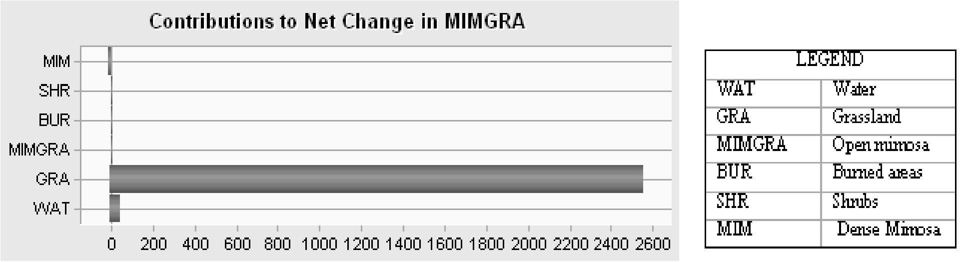


Figure 4. 12 Graph showing the classes contributing to net gain of the open mimosa during a period from 1994-2005

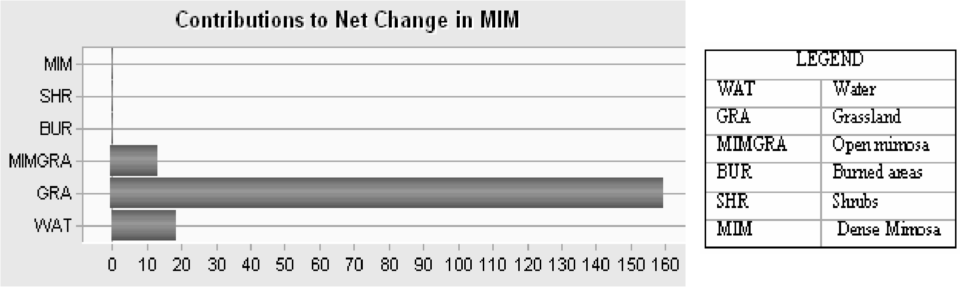


Figure 4. 13 Graph showing the classes contributing to net gain of the class Dense mimosa during a period from 1994- 2005

Figure 4.14 is a Boolean map that shows the portion of the study area that has undergone transition from class grassland to open mimosa. It is obvious that there is only one way transition from the class grassland to mimosa (open or dense) but the vice versa is absent.

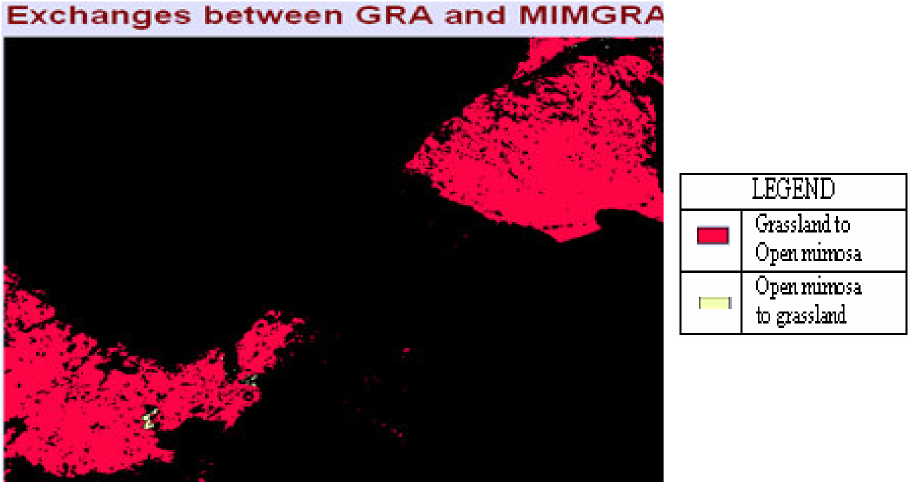
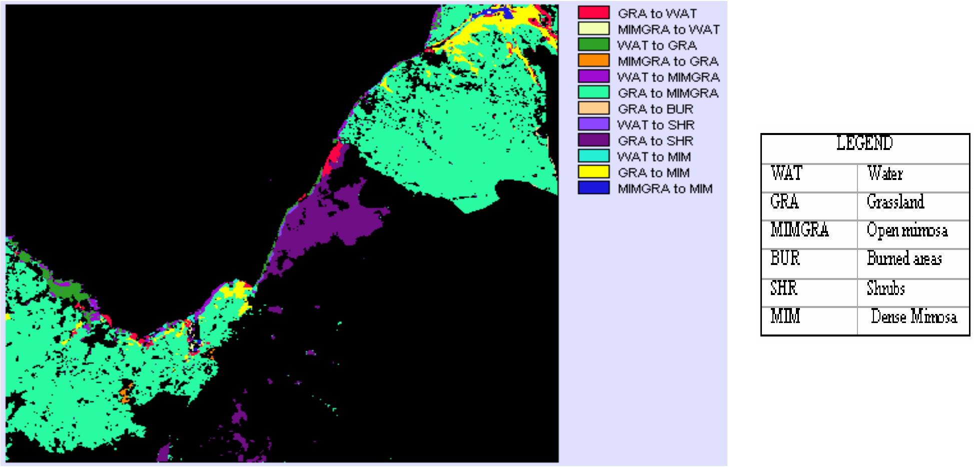


Figure4. 14- Boolean maps showing the exchanges between the classes grasslands and open mimosa during 1994-2005

Figure 4.15 shown below is a pictorial representation that summarises the various cover classes that has undergone transitions from one to the other during a period from1994-2005

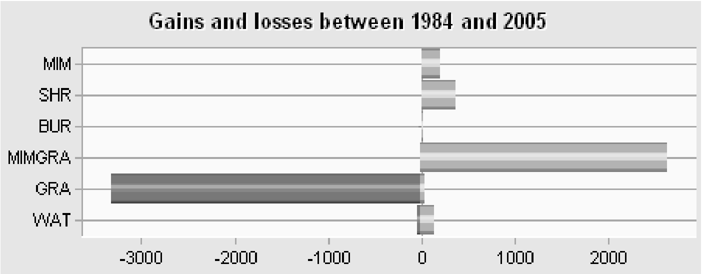


LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure 4. 15- Map showing the overall transitions between the various classes during the period 1994-2005

LCM MODELER 1984-2005

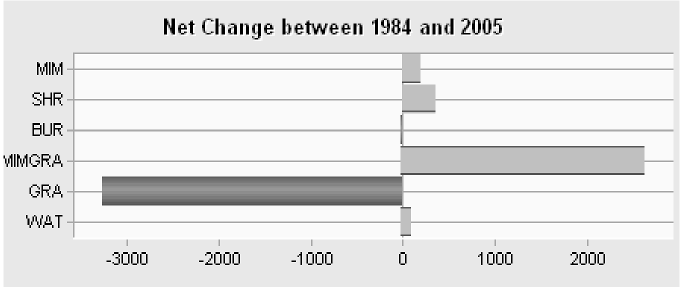
On comparing the results of 1984-94 and 1994-2005 it is obvious that the change experienced by the various cover classes does not follow a regular pattern. The most evident being the exchanges have taken place between the classes grasslands and open mimosa. The transition between the various cover classes during a period from 1984-2005 were taken into account in order to quantify and observe the overall changes experienced by various cover classes. Figure 4.16 shows the overall gains and losses experienced by the various cover classes during this span of 20 years.



LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure4. 16- Graph showing the overall gains and losses experienced by the various classes. From 1984-2005

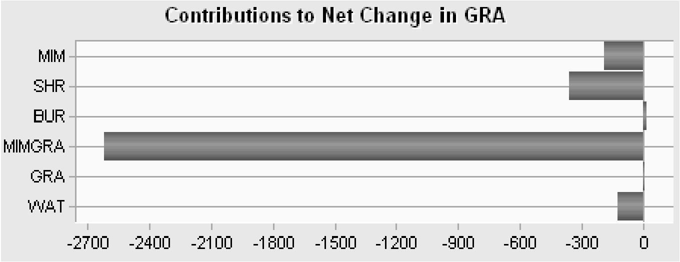
Similarly the net changes (gain and loss in ha) experienced by various cover classes on the whole are shown in figure 4.17



LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

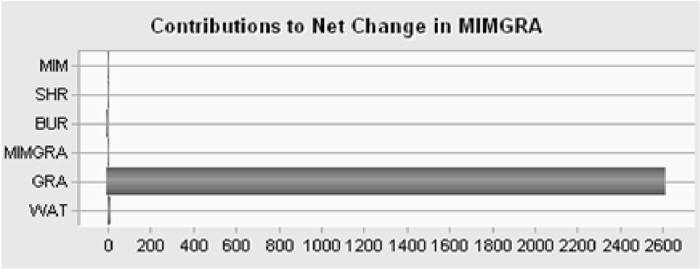
Figure4. 17- Graph showing net gains and losses (ha) experienced by the various cover classes from 1984- 2005

Figures 4.18, ,4.19, 4.20 and 4.21 shows those cover classes that has contributed to the net change in grasslands, open mimosa, dense mimosa and shrubs respectively during a period from 1984- 2005.



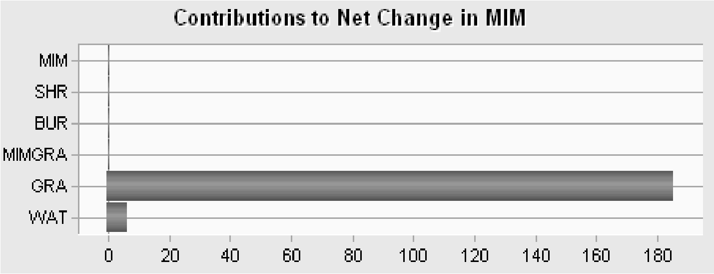
LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure4. 18- Graph showing the cover classes that has contributed to net loss of grasslands(ha) during a period from 1984-2005



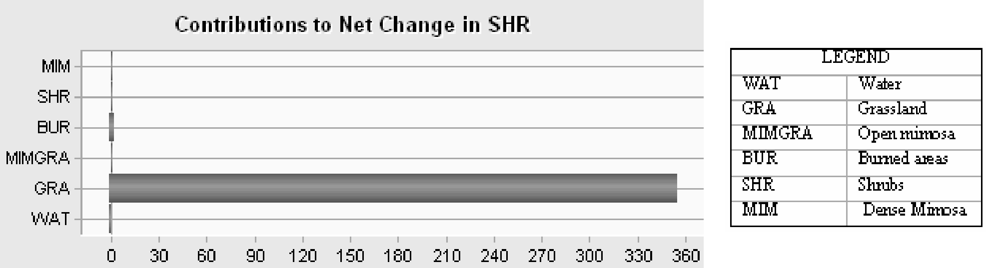
LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure4. 19- Graph showing the classes that has contributed to net gain the class open mimosa(ha) during a period from 1984- 2005



LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

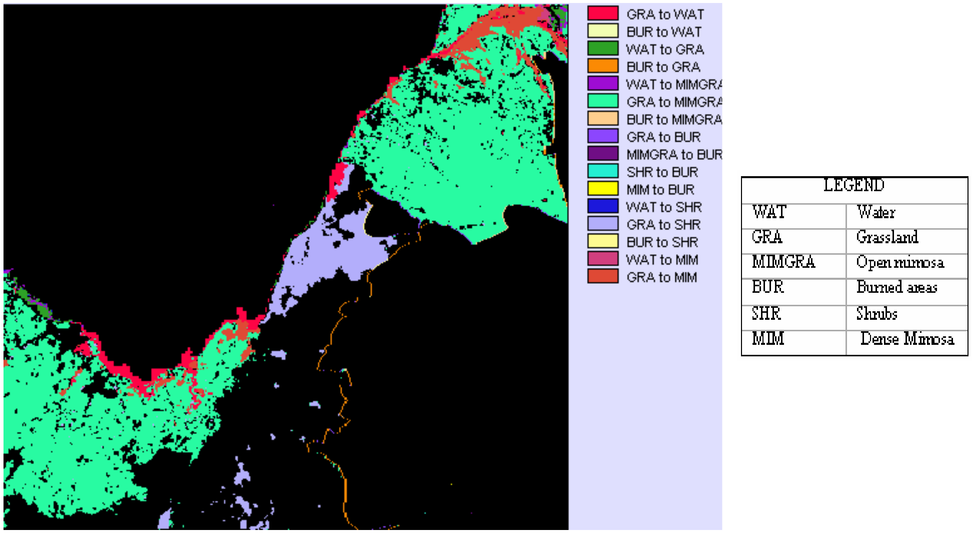
Figure4. 20- Graph showing those classes that have contributed to increase in dense mimosa (ha) during a period from 1984-2005



LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure4. 21- Graph showing those classes that have contributed to increase in shrubs (ha) during a period from 1984-2005.

Figure 4.22 shown below is a pictorial representation that summarises the various cover classes that has undergone transitions from one to the other during a period from 1984-2005.



LEGEND	
WAT	Water
GRA	Grassland
MIMGRA	Open mimosa
BUR	Burned areas
SHR	Shrubs
MIM	Dense Mimosa

Figure4. 22- Map showing the overall transitions between the various classes during the period 1984-2005

4.3. Cross classification

CROSSTAB module in Andes was performed in Idrisi Andes between land cover images of 1984-94, 1994-2005 and 1984-2005.

CROSSTAB 1984-94

The CROSSTAB module was performed for the images of 1984 and 1994 which gave two outputs a cross correlation image and a cross tabulation (table 4.2). The table shows the number of cells under each cover class in 1984 that has remained the same or has undergone change in 1994. It should be noted that the columns represent the land cover classes of 1984 and rows represent that of 1994

	1984							
	Classes	**Water**	**Grassland**	**Open mimosa**	**Burned areas**	**Shrubs**	**Dense Mimosa**	**Total**
1994	**Water**	57438	2472	0	0	0	0	**59910**
	Grasslands	831	58700	0	0	0	0	**59531**
	Open mimosa	0	524	1	0	0	0	**525**
	Burned areas	0	0	0	38399	1	1	**38399**
	Shrubs	0	0	0	0	1	0	**1**
	Dense Mimosa	0	0	0	0	0	1	**1**
	Total	**58269**	**61696**	**1**	**38399**	**1**	**1**	**158367**

Table4. 2- Cross tabulation of land cover 84 (columns) against land cover 1994(rows).

The table shows that most of the changes have taken place near to the diagonals which indicate the disposition of phenomenon to be incremental rather than violent ones.

1994-2005

Similarly a CROSSTAB module was performed for land cover images of 1994-2005. The cross tabulation result is shown in table 4.3

	1994							
	Classes	**Water**	**Grassland**	**Open Mimosa**	**Burned areas**	**Shrubs**	**Dense mimosa**	**Total**
2005	**Water**	58212	674	51	0	0	0	**58937**
	Grasslands	787	24635	78	0	0	0	**25500**
	Open mimosa	599	28547	238	0	0	0	**29384**
	Burned areas	0	0	0	38399	1	1	**38399**
	Shrubs	105	3899	3	0	0	0	**4007**
	Dense Mimosa	207	1776	154	0	0	0	**2137**
	Total	**59910**	**59531**	**525**	**38399**	**1**	**1**	**158367**

Table4. 3- Cross tabulation of land cover 94 columns against land cover 2005 rows.

Similarly the cross tabulation result from 1984-2005 are shown in table 4.4

	1984							
	Classes	**Water**	**Grassland**	**Open Mimosa**	**Burned areas**	**Shrubs**	**Dense Mimosa**	**Total**
2005	**Water**	57143	1794	0	0	0	0	**58937**
	Grasslands	321	25179	0	0	0	0	**25500**
	Open Mimosa	703	28681	1	0	0	0	**29384**
	Burned areas	0	0	0	38399	1	1	**38402**
	Shrubs	29	3978	0	0	0	0	**4007**
	Dense Mimosa	73	2064	0	0	0	0	**2137**
	Total	**58269**	**61696**	**1**	**38399**	**1**	**1**	**158367**

Table4. 4- Cross tabulation of land cover 84 (columns) against land cover 2005 (rows).

Taking into account the changes between the land cover classes for all the three years the overall changes can be summarised as shown in table 4.5

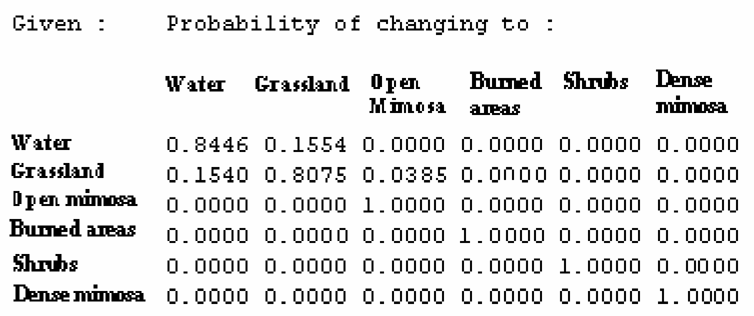
				Change(ha)		**Increase**		**Decrease**	
	1984(ha)	**1994(ha)**	**2005(ha)**	**84-94**	**94-05**	**84-94 %**	**94-05 %**	**84-94 %**	**94-05 %**
Water	5244.2	5391.9	5304.3	147.69	- 87.5	2.8			1.6
Grassland	5552.6	5357.7	2295	-194.8	- 3062.7	-	-	3.5	57.1
Open Mimosa	0	47.2	2644.5	47.25	2597.3	Na	550.27		
Burned areas	3455.9	3455.9	3455.9	-	-				
Shrubs	0	0	360.6	-	360.6				
Dense mimosa	0	0	192.3	-	192.3				

(Na-Not applicable)

Table 4. 5- Table showing the overall changes that has taken place between the various years

4.4. Prediction using Markov Chain Analysis

Markov analysis was performed for the multitemporal land cover images of 1984-94 predicting to 2005 and 1994-2005 predicting to 2015 as shown in table 4.6 and 4.7 respectively



Given :	Probability of changing to :					
	Water	**Grassland**	**Open Mimosa**	**Burned areas**	**Shrubs**	**Dense mimosa**
Water	0.8446	0.1554	0.0000	0.0000	0.0000	0.0000
Grassland	0.1540	0.8075	0.0385	0.0000	0.0000	0.0000
Open mimosa	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
Burned areas	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
Shrubs	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
Dense mimosa	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

Table 4. 6- Markov prediction to 2005 based on land cover images of 1984-1994

According to the land cover images of 1984 and 1994 the prediction by markov analysis states that the probability of grasslands to remain as grasslands is 80% and that of grasslands to change to open mimosa is only 4 %in the next 10 years. Based on the transition matrix as shown in table 4.6 a set of markov conditional probability images were generated. The spatial extent of classes grasslands and open mimosa predicted to 2005 according to markov matrix is shown in figure 4.23 and 4.24 respectively. This is compared with the classified ASTER imagery of 2005 (shown below) to observe to what extent the prediction by markov chain is reliable.

On comparison of the results we find that there is high discrepancy between the classified image of 2005 and the projected markov conditional probability images especially for the classes open mimosa and grasslands. It is evident from the classified ASTER image of 2005 that the area under mimosa has increased nearly 5 times (table 4.5) when compared to that of 1984 and 1994 images. This proves that markov chain has underestimated the area likely to be infested by mimosa in 2005 based on the probability of transition of various cover classes to mimosa between 1984 -94.

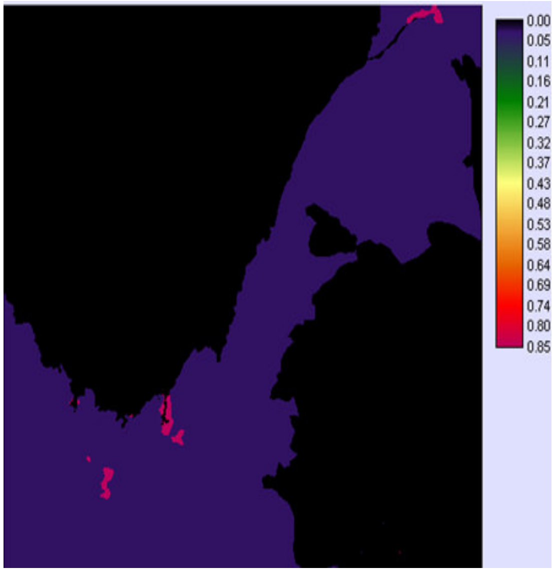


Figure4. 23- Map showing the probability of spatial spread of open mimosa projected to 2005 according to markov conditional probability matrix

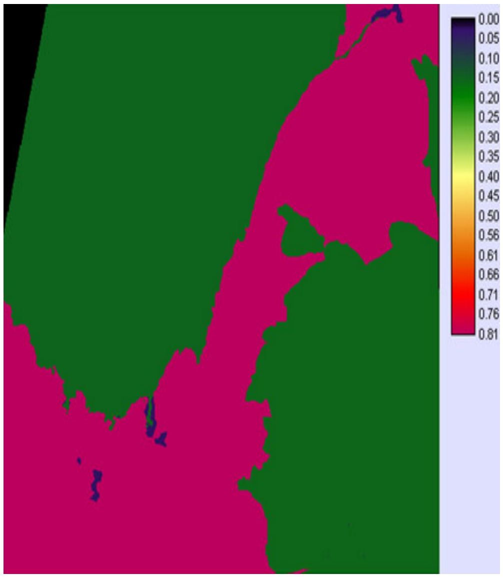
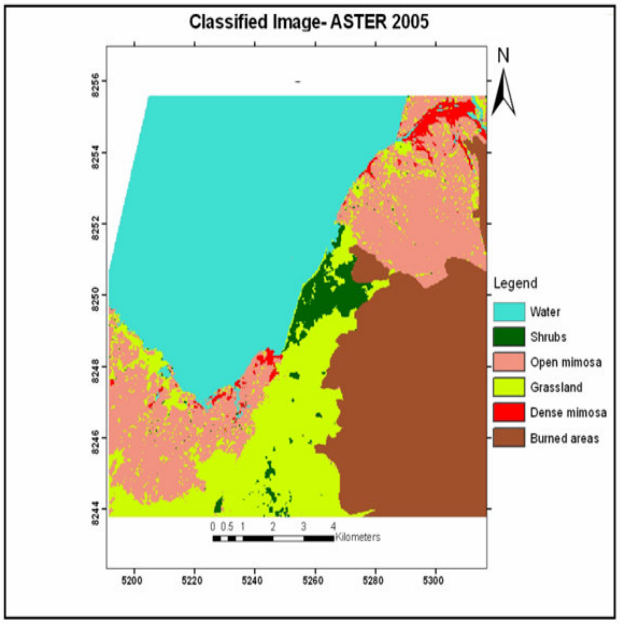
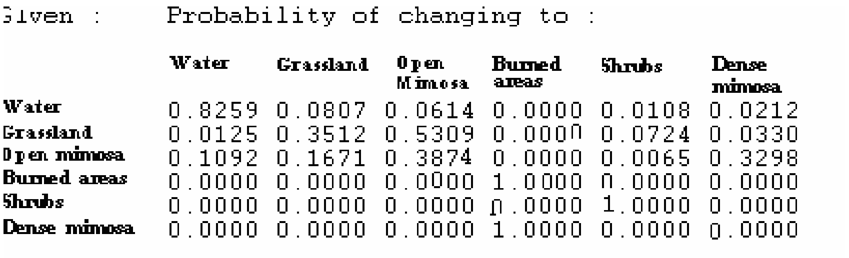


Figure4. 24-Map showing the probability of spatial extent of grasslands projected to 2005 according to markov transition probability matrix.



Similarly based on the land cover images of 1994 and 2005 a land cover change was predicted to 2015. The markov transition probability matrix is shown in table 4.7.



Given : Probability of changing to :

	Water	Grassland	Open Mimosa	Burned areas	Shrubs	Dense mimosa
Water	0.8259	0.0807	0.0614	0.0000	0.0108	0.0212
Grassland	0.0125	0.3512	0.5309	0.0000	0.0724	0.0330
Open mimosa	0.1092	0.1671	0.3874	0.0000	0.0065	0.3298
Burned areas	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
Shrubs	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
Dense mimosa	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000

Table 4. 7–Markov prediction to 2015 based on land cover images of 1994 and 2005

According to this transition matrix we find that the probability of grasslands to remain as grasslands is only 35% in the next 10 years where as the probability of grasslands to change to mimosa infested areas is as high as 53%. Similarly the probability of class open mimosa to change to class dense mimosa is 32%.

Based on the markov transition matrix shown in table 4.7 a set of markov conditional probability images were generated for each land cover class. The areas that are likely to be invaded by classes open mimosa and dense mimosa in 2015 is show in figure 4.25 and figure 4. 26.

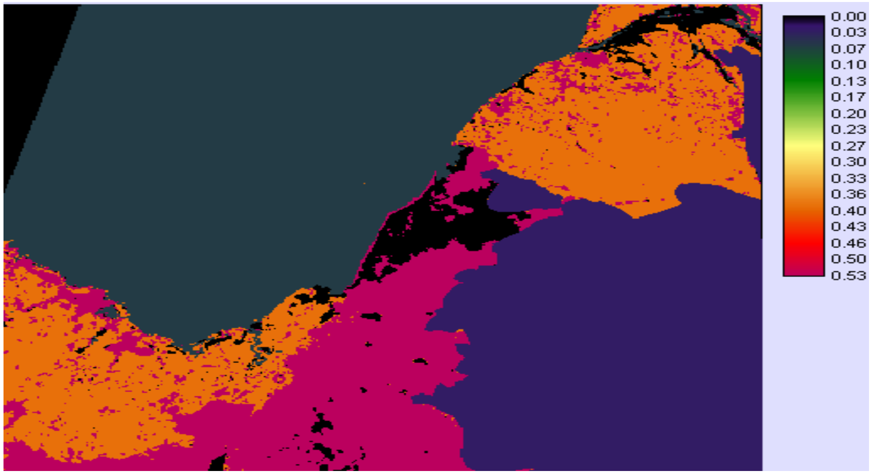


Figure4. 25- Map showing the probability of spatial spread of open mimosa projected to 2015 according to markov conditional probability matrix

It can be seen from the above figure that according to Markov transition probability the grasslands are highly vulnerable to infestation by *Mimosa pigra* in the next 10years. The probability of the invasive to encroach into the grasslands are as high as 53% (table4.7). However it can be noticed that those areas which were originally classified under dense mimosa and shrubs are not represented in the map and the value is shown as 0.

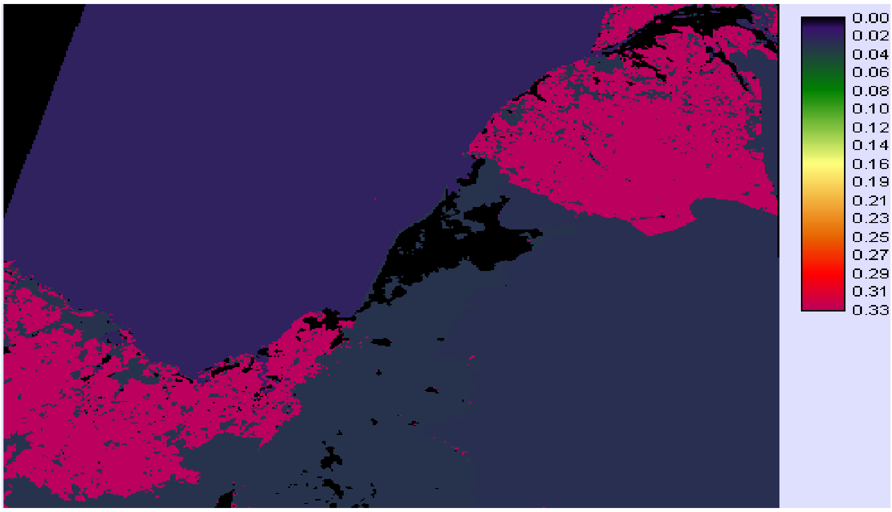


Figure4. 26- Map showing the probability of spatial spread of dense mimosa projected to 2015 according to markov conditional probability matrix**.**

The above map indicates that the probability of open mimosa to convert into thickets of dense mimosa is as high as 33% (table 4.7) in the next 10 years. However is should be noticed that according to the table the probability of dense mimosa to remain as dense mimosa is 100% but this is not represented in the image. As in the previous image the areas originally represented by classes dense mimosa and shrubs is shown in black and has a probability of 0.

4.4.1. Test of independence

The tests of independence were carried out between two land cover images 1984-94 and 1994-2005 as shown in table 4.8

Land Cover	Degrees of freedom (df)	K^2	P value
1984 - 94	25	15361	0.000
1994 – 2005	25	14324	0.000
1984 – 2005	25	30175	0.000

Table4. 8- Summary of the Karl Pearsons $\chi 2$ between 1984 - 1994 and 1994 - 2005 and 1984 -2005

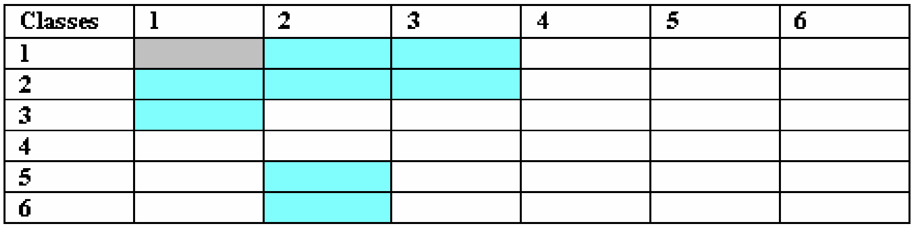
The P value indicates that the test value is highly significant statistically. This is because the chi square results showed very high values. This indicates high dependency between all the three land cover images viz 1984-94, 1994-2005 and 1984-2005. Hence in all the three cases the null hypothesis of independence between any two land cover images can be rejected.

4.4.2. Test of Markovian dependence

Since it was proved that there was high dependency between all the three land cover images the next step was to calculate for markovian dependence between them. A K^2 goodness of fit test was performed using equations shown in section 3.7.2 (pg 36). The computed K^2 gave a very high value of 115610 which was much higher than the table value with degrees of freedom 25. Thus we reject the hypothesis that the phenomenon under consideration showed markovian dependence.

4.4.3. Test of significance

A test of significance was performed by comparing the proportions of each cover class for the years 1984 -94 and 1994 -2005. The null hypothesis was that the proportions of each class are equal and the alternative hypothesis was that the proportions are not equal. The proportions of each class was calculated from the cross tabulation and the z value was computed for each class. It was found that the computed z value was much higher than the table value hence the null hypothesis was rejected which means that the proportions differ significantly. Table 4.9 shows those classes which differ significantly which is represented by blue and those classes which are do not differ significantly represented by grey. The blank columns indicate that the value was 0 and there was no test carried out.



Classes	1	2	3	4	5	6
1	▨	🟦	🟦			
2	🟦	🟦	🟦			
3	🟦					
4						
5		🟦				
6		🟦				

Table4. 9- Table showing those classes that has changed in proportions when comparing the land cover images of 1984-94 and 1994- 2005.

5. Discussions

5.1. Delineation of *Mimosa pigra* invaded areas using multitemporal dataset

Supervised classification of ASTER 2005 and LANDSAT 1994 and 1984 has revealed the fact that over the years, the aggressive alien shrub, *Mimosa pigra* has been invading the Park area to a considerable extent by drastically reducing the area under grasslands. Six cover classes have been assigned for the purpose of classification. The overall accuracy was 74.4 % and the user's accuracy and producers for the classes of interest (open mimosa and dense mimosa) was 70 and 75% and 78 and 75% respectively. The confusion matrix reveals that there was some spectral confusion between grasslands and open mimosa since both classes had grassland in common (though the grass was dry in most areas). However it was impossible to distinguish pure mimosa areas from the grasslands since the growth of the invasive alien in terms of spatial extent was sporadic depending upon the availability of water and sunlight. Hence it was found to grow in varying densities mixed with grasslands within an area. The class open mimosa was assigned since it has been proved that once an area is infested by mimosa even though to a small extent the probability of changing back to pure grasslands is almost negligible. So those areas can be considered as already invaded by mimosa.

The satellite image of 1984 does not detect any mimosa. This may be due to the fact that in 1984 the area under mimosa was so small that LANDSAT could not detect it with a spatial resolution of 30m. Before 1980 there was only one infestation occupying approximately 2 ha at the head of the Nampongwe stream, which flows through Chunga Lagoon (Douthwaite & van Lavieren, 1977; Sheppe & Osborne, 1971)**.** The LANDSAT image of 1994 could detect 47.25 ha of mimosa. The results obtained through personal communication of a study which is in progress on shrub encroachment into grasslands in Lochinvar National Park conducted by Gennet (2007) detects 241.83 ha of *Mimosa pigra*. However aerial survey conducted by Thompson (1986) in late 80 s reveal that mimosa was spreading throughout the park and showed signs of becoming an invasive where it occupied approximately 100 ha He also reports that in 1994 few areas of mimosa mixed with dry grass was identified along the Nampongwe stream and the Mainda channel.. This difference in results on the extent of mimosa can be attributed to reasons like difference of spatial resolution of the sensors and season of acquisition of the imagery. Assuming that the aerial survey has produced the most accurate results, in this study LANDSAT has underestimated the extent of area under mimosa in 1994 whereas the study by Gennet (2007) has overestimated the same. The most obvious reason for the underestimation of results was because of the discontinuous and mixed growth pattern of mimosa with grass and the spatial resolution of LANDSAT. The comparatively low resolution (~30 meters) of the imagery which is most accessible but limits the ability to detect individual plants and new outbreaks, only large established patches can be readily identified. It could only detect those areas where mimosa growth is fairly dense found mixed with grass where as aerial surveys can give more spatially specific results.

Whereas the classification results of ASTER 2005 identifies two classes of mimosa which are open mimosa and dense mimosa. It also clearly shows that the area especially near the lagoon was heavily infested with mimosa. This is because the spatial resolution of ASTER is 15 m which allows for better identification of the species and also by 2005 the extent of spread of mimosa was widespread and it clearly showed up to be an invasive plant. The field observation also corroborates the classification result. Areas that were classified as dense mimosa near to the Mainda channel and Nampongwe stream were inaccessible due to the thick impenetrable growth of the plant. Those areas classified as open mimosa, was found to grow in varying densities such as dense and fairly dense which were impenetrable thickets , medium density where it was crowded and thinly populated where the spacing between the plants was quite far apart. In order to delineate the pure patches of mimosa from grasslands high spatial resolution imagery would be required like aerial photographs, QUICKBIRD or IKONOS.

It was interesting to note that mimosa is found up to the fringes of the lagoon but the density of population was much less in those areas that are permanently under water. There are only very few mimosa plants thriving in prolonged water logging conditions. It is found to survive best in those areas where water is readily available but not very successful when the whole plant is in water. The lands subjected to seasonal inundation and swamp land are considered to be the best habitats for mimosa to grow (Lonsdale, 1993). Studies show that mimosa probably might not be a problem in those areas if the annual rainfall is more than 2250mm and if the area is flooded for very long periods because it cannot withstand prolonged water logging conditions (Janzen, 1983). Hence as evident from the classified image of 2005 most of the mimosa is found on the seasonally inundated floodplains where the conditions are conducive for its proliferation since these areas provide moist conditions optimal for its growth. Moreover mimosa is very tolerant of seasonal inundation due to its ability to produce adventitious roots. Another striking feature that has been noticed is that it is absent in those areas where the shrubs such as *Dichrostachys cineraria* are found. Though *Mimosa pigra* is known to be a fierce competitor it cannot compete with plants that have rapid growth and well established root systems. It is also highly intolerant to shade and requires full sunlight for its survival (Janzen, 1983). So probably that may be the reason why mimosa has not been successful to thrive and compete in those areas where shrubs are present.

This study reveals the fact that grasslands are subjected to tremendous pressure through the invasion of mimosa and spreading of shrubs in the past decades. Shrubs have been encroaching into the grasslands from the inlands and are moving towards the lagoon where as *Mimosa pigra* is invading the areas near to the lagoon and is moving towards the inlands. As mentioned earlier another interesting feature observed is that mimosa is spatially segregated from the shrubs and found mostly on the western and eastern side of the study area while the shrubs can be distinguished as a clear patch in the middle. In addition to the above mentioned reasons there may be various factors contributing to the spread and spatial segregation of *Mimosa pigra.* The most evident reason seems to be associated with the direction and extent of flooding, difference in elevation and animal movement which aids in seed dispersal to far off places. Lochinvar National park is almost flat having an elevation of 981m above sea level.

The floodplain is proper flat and extensive, gently sloping area that is seasonally inundated with Kafue river water (Ellenbroek, 1951). The gradient at the edge of the floodplain at some places is marked by relatively sharp rise of several metres; in other places the rise is imperceptible. In contrast to this overall lack of gradient several types of local relief are of great ecological importance. The Kafue river at low water is about 3- 5m m below the top of its banks (Sheppe & Osborne, 1971). Often on the banks of present and former channels are natural levees which may be 2 m higher than the adjoining floodplains. These topographically higher areas called levees are found scattered within the park and is occupied by tall grasses such *as Echinochloa sp, Vossia cuspidate* except for in scattered places where it is occupied *by Acacia albida* and *Dichrostachys cineraria* (Chabwela & Mumba, 1998). The lowest part of the floodplain usually is the zone next to the levees (Sheppe &

Osborne, 1971). The levees consist of more or less elevated parts and are not flooded in hydrologically normal years. So during the peak seasons of flooding the flood water extends almost down south beyond the termitaria zone owing to the flat terrain but avoiding the levees.

During field data collection it was noticed that the areas where are shrubs are found there is a slight elevation in the topography and this feature resembles to that of natural levees. Not every year this particular area gets flooded since water spreads along the flat terrain and move inwards. So probably that may be also be one of the reasons why mimosa could not be found there since the chances of seed dispersal through flooding waters are very less and even if it was established it must have failed to out compete with vigorous growing shrubs. This is discussed in detail in section 5.3.

5.2. Change detection studies

On comparing the cross tabulation results of 1984-94, 1994-2005 it is clear that there has been such a drastic change in the land cover especially for classes like grasslands and open mimosa. It can be seen that the area under pure grasslands has been invaded by mimosa and there was a dramatic decrease of 5357.5 ha of grasslands in 1994 to 2295 ha in 2005 and the overall loss of grasslands from 1984-2005 was 3257.6ha. Similarly the area under the class open mimosa has increased from 47.5 ha in 1994 to 2644.5 ha in 2005 and the overall increase from 1984 to 2005 for both the classes open mimosa and dense mimosa is from almost 0 to 2836.8 ha and as mentioned in the previous sections most of this transition has taken place at the expense of grasslands.

The results from the cross tabulations of three years shows that most of the activities took place along the diagonals except for the classes open mimosa and dense mimosa which manifested sudden changes. This alarming increase of expansion of mimosa was least expected and the results were compared with the aerial surveys conducted by Thompson (1986) and hydrological studies done by Mumba (2003). They report that in 1980 there were only 2 ha of mimosa and a survey conducted in 2003 shows that the area under infestation has increased to more than 2500 ha. It is interesting to note that the result obtained through this study detects 2836.8 ha of mimosa in 2005 which corresponds to the above studies which estimates more than 2500 ha of mimosa in 2003. However it should be understood that there would be some variation regarding the estimation of the exact spatial extent of mimosa infestation within the study area because of various sources of error like that from sensors, sampling and classification.

In Australia mimosa was restricted to the wet dry tropics of the northern territory, where its population has followed a classical pattern of introduced organism (Lonsdale, 1993) with a lag phase of 60 years followed by a dramatic population explosion since late 1970s (Lonsdale & Abrecht, 1988). Studies from the Mekong Delta shows that in May 2000, the area of infestation was 490 ha and it had increased to 1846 ha in May 2002 (Triet *et al* ,2004). Here the rates of invasion were very high where it doubled in its area almost every year during 2000-2002. The comparison of various studies proves the aggressive capability of the invasive to rapidly colonise the area within a short period of time. There may be several reasons attributed to this sudden expansion which is explained in the next section

5.3. Reasons for the spread of *Mimosa pigra*

It is evident that the infestation by *Mimosa pigra* which began as a small unnoticeable problem in the 1980s has now been spreading through the park so rapidly thus disturbing the diverse and fragile wetland ecosystem. An interesting question to be raised here is why has mimosa been so successful in the park and what are the probable factors contributing to the successful invasion of mimosa. In this section the probable reasons that have contributed to the invasion of mimosa are discussed below

a) Change in flooding regime

The annual flooding of the Park has been recognized as a definite requirement for preserving the ecological balance of the area. As mentioned earlier the Park is flooded mainly by three sources which are local rainfall, floodwaters from the Kafue river and the streams and creeks. The occurrence of high flood and low flood is regular through successive years, but the extent of floodwater and its speed with which it rises and recedes vary from year to year (Rees, 1978 b). The Kafue Gorge dam and the Ithezi- tezhi dams have affected the extent and timing of flooding and water levels of the Kafue Flats (Sheppe & Osborne, 1971). The Kafue gorge dam delays the fall in water levels on the Kafue Flats, so that flood conditions persist at the end of dry season of the eastern end of Kafue Flats (Douthwaite & van Lavieren, 1977). Flood levels, total area flooded, as well as the duration of flooding are mainly defined by the inflow at Ithezi-tezhi (Ellenbroek, 1951). The Ithezi- tezhi dam releases water relatively constant rate to assure a continuous supply to the gorge power plant, thus greatly reducing the seasonal fluctuations in volume of water on the flats and consequently reducing the height and extent of the floods. Much of the former floodplain primarily in the western parts of the Flats are no longer flooded (Sheppe & Osborne, 1971). Flooding within the park, vary in magnitude in magnitude from year to year, occurred in the pre-Ithezi -tezhi period, depending on the flow into the river from the catchment. This was uncontrolled flooding. Flood regime has a major influence, the speed of rising of water, its withdrawal, its depth and duration and length during the dry period. The peak flood at Lochinvar is at the end of April and floods starts to recede at Lochinvar from May and reach their lowest point in November. The construction of the both the Kafue Gorge and mainly the Ithezi- tezhi dam has changed the extent and timing of peak flooding and the water levels reached in the Park.

Studies conducted by WWF in 2002 reveals that the average annual flooding before the construction of the dam was significantly higher than after the construction of the dam and consequently a large area that used to be flooded remains dry all the year round. Another result of hydropower installations is the appearance of unnatural floods during the dry season, June to October, as a result of water release from the dam at the Ithezi-tezhi. The peak flood now occurs in July instead of March (WWF, 2002). Releases from Itezhi-tezhi dam are very different to the historical flows experienced within the Kafue River. The smooth annual rise and fall in discharge has been replaced by sudden increases in flow as large volumes of water are released from the dam. These are followed by equally rapid declines in discharge as the large releases are terminated.

Studies conducted by Mumba (2003) shows that the pre-dam period is considerably wetter with over twice the annual flow and this is illustrated in figure 5.1 which shows the comparison of the monthly discharges at Nymba hydrological station (nearest station to Lochinvar National Park) prior to the regulation and after the regulation at the Ithezi-tezhi dam. The mean monthly discharge gives a direct indication of the release of water into the Park hence it gives an idea of the extent of flooding. It also illustrates that the following regulation, dry season flows had increased while peak flows during wet season were generally reduced. Results from the study revealed that there was 62% increase in dry season flows and 35% reduction in peak flows following the regulation. The monthly water discharges at

Nymba hydrological station were also obtained during a period from 1980-2005 as shown in figure 5.2. As evident from the graph we can notice that there is an overall trend of decreasing water discharges over the years. These figures indicate that the flooding within the park has definitely decreased after the construction of the Ithezi-tezhi dam.

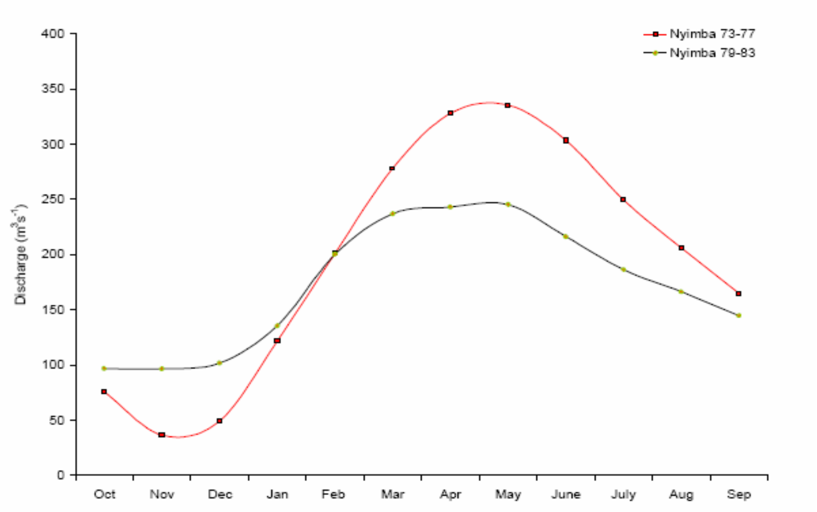


Figure 5. 1-Mean monthly discharges at Nymba (pre Ithezi- thezi 1973 -77 and post Itehzi-thezi 1979-83) (Courtesy- Mumba, 2003)

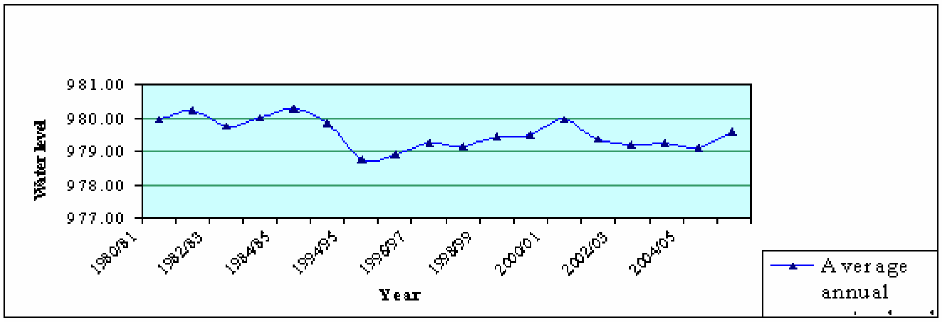


Figure 5. 2- Graph showing the water levels at Nymba from 1980- 2005**.**

This proves that there has been a change in flooding regime that affected the ecological stability of the area .Though there has been many negative impacts due to the construction of the dam one of the most prominent one in terms of ecological significance is the change in the vegetation patterns and invasion by inedible shrubs as the land is no longer flooded (Centre for Ecology and Hydrology, 2001). According to (Acreman *et al.*, 2000)decrease in flooding can lead to the reduction of the productivity of floodplain grassland by

- reducing the value of hinterland grazing, as the total carrying capacity of the dry season/wet season system is reduced
- reducing the fertility and hence primary productivity of floodplains, as sediment loads are reduced
- replacing nutritious floodplain grass species with less nutritious dryland species
- increasing the risk of overgrazing in the floodplain due to the loss of seasonal vegetation.

Under natural flooding conditions the system was highly dynamic. Plant communities exhibited partial monthly successions and annual variations dependent on the changing flood regimes. Historically vegetation associated with the Kafue Flats floodplain had been able to cope with low flow conditions that naturally occurred during the dry season and was reliant on natural high flow conditions that occurred in the wet season (Douthwaite & van Lavieren, 1977). This is based on the assumption that flow conditions within the floodplain that were a normal characteristic of it whether extreme, variable or unpredictable, are the ones to which vegetation was adapted to. Vegetation within the Flats was flood dependent relying on well timed floods for the provision of regeneration and successful establishment of seasonal vegetation (Mumba, 2003).

The Kafue lechwe follows the flood line and their changing distributions coincide with the changes in flood level and this in turn coincides with areas where the nutritional levels of grasses are high. Rees (1978 a) reports that the floodplain grasslands harbours mainly sweet grasses for the lechwe. When the floodplain is maximally inundated the lechwe are forced to move beyond the termitaria zone and when the flood recedes it comes back to the floodplain. He also reports that when this natural flooding regime has changed there appeared to exert a strong influence over the representation of the different species of grasses and their rate of growth. This has led to the replacement of the more nutritious grasses with less nutritious dryland species. This might have favoured the growth and successful establishment of mimosa seedlings since there is less competition with the robust and quickly growing native grasses. A study carried out by Chabwela and Siwela (1986) showed that the lack of water limited the occurrence of palatable species such as *Echionochloa* sp, *Vossia cuspidate* and *Acroceras macrum*. Instead woody plants, mainly *Dichrostachys cinerea* and *Mimosa pigra*, began to invade the flats. Lonsdale (1993) suggests that like many other hard-seeded woody shrubs, disturbance that temporarily eliminates competing vegetation is the key to successful *M. pigra* establishment (Holmes, Macdonald & Juritz 1987; Paynter *et al*. 1998). The overgrazing by lechwe might also have had an influence for the successful establishment of mimosa.

As evident from the above studies that the extent of flooded area has decreased this means that during the wet season the lechwe will not move far off south (beyond the termitaria zone) as during the normal flooding regime. Thus the area near to the floodplains is subjected to more grazing pressures by lechwe throughout the year leaving behind very little grass enabling mimosa to readily establish and expand rapidly in the absence of competition. Overgrazing and disturbance by feral water buffalo *Bubalus bubalis* has been blamed for assisting the rapid expansion of *M. pigra* in the Northern Territory of Australia during the 1970s (Cook *et al.*, 1996; Lonsdale & Abrecht, 1988). Furthermore, Lonsdale (1993) provided evidence that the rate of expansion of *M. pigra* has declined following a water buffalo eradication campaign in north Australia. Thus it can be concluded that the alteration of the natural hydrological regime has led to replacement of the nutritious grasses with dryland species and this combined with the absence of competitive floodplain pastures due to overgrazing by lechwe has triggered a disturbance in the natural ecosystem that has favoured the colonization by the invasive shrub .

One of the major principal ingredients for the successful establishment of mimosa are moist or wet soils (Miller & Lonsdale, 1987). The plant could take advantage of the absence of prolonged water logging conditions and the increased dry season flooding. The elimination of flood on much of the flats, has permitted the invasion of the floodplain by woody plants that formerly were killed by floods (Sheppe & Osborne, 1971). A study conducted in Vietnam by Triet *et al* (1994) reveals that the density of outbreaks of *Mimosa pigra* was less in those areas that had longer period of inundation**.** Glasshouse experiments suggest that permanent inundation would prevent seedling recruitment (Shibayama *et al*, 1983). Several consecutive above average wet seasons can inhibit the germination of mimosa seeds to some extent. Whilst they need moist soil to germinate, excessive water logging reduces the rate of seed germination possibly by rotting of the seeds or via oxygen deprivation. This phenomenon has been observed in the Northern Territory in regions of the Arafura Swamp and on the Phelp River floodplain (Ashley, 2001). A study conducted by Sheppe (1985) in Lochinvar reports that thickets of plants that require permanently moist soil are becoming established along the shore of the new water bodies. Flow disturbance is known to provide the stimulus for the establishment of opportunistic plants particularly alien invasive species Rees (1978 c).

Mimosa seeds are dispersed mainly through water. Studies conducted by Lonsdale in Australia suggest that one of the major factors contributing to the dramatic advance by mimosa is flood waters. The seeds of mimosa can float on water for extended periods (Miller *et al* 1981). Mimosa seeds are covered by hairy coats that help them to float on water. The most heavily infested areas are along the watercourses such as rivers, streams and areas that are affected by flooding. From the point of view of mimosa expansion the most important feature of flooding is its horizontal extent – the area covered, the length of the time that each part of the Park is under water.

The actual area liable to flooding is of prime importance for the establishment of relationships between water level, water storage and extent of flooded area and plant growth (Ellenbroek, 1951). But unfortunately no reliable data on these questions are available though crude estimates of area flooded are available. This is because of the complex pattern of advance of floods no single rate figure would be adequate. Sheppe also reports that during the study it was observed that on one day the flood was approaching its maximum extent at Lochinvar, the water was advancing up a dry drainage channel at the rate of about a meter per hour, but at nearby point in a steeper slope there was no perceptible advance in 24 hrs. In years of low floods the river bank levees remain exposed, and the flood hardly reaches the termitaria but in years of high floods the levees are covered though to a lesser extent and duration. But generally during flooding the water spreads to eastern and the western sides of the park beyond the termitaria zone because of the flat terrain leaving the small portion of levees where the shrubs are found to be growing. This is because the levees are higher in elevation by few cms which diverts the water to the sides of the floodplain. A study conducted by Rees in 1978 reports that in levees the height above the zero water level in is 0.5 and lower and those of the floodplains is 0.5 to 3.5.

b) Environmental conditions

There may be various environmental factors combined with other factors that have contributed to the sudden expansion of mimosa. Mimosa is a drought resistant plant and can withstand prolonged periods of dry conditions. Its seeds can remain active in the ground for 10years and when favourable conditions come they can germinate

(Lonsdale, 1993). The metrological data of Lochinvar National Park indicates that from a period of 1980 to 2005 the overall trend of rainfall pattern has been decreasing but that of temperatures remain almost the same. This shows that the area has been receiving lesser rainfall whilst the temperatures remaining high which means that there has been a slight variation in the start and duration of local flooding .This combined with the insufficient water release from the dam has contributed to lesser extent of flooded area during the wet season and presence of moist conditions during the dry season due to the regulated artificial water release from the dam have added to the advantage of the expansion of woody invasive, *Mimosa pigra*. Mimosa is found to tolerate wide range of soil and moisture conditions. It generally prefers moist soil conditions and thrives well in seasonally inundated floodplains and during dry season and is actually drought resistant (Miller *et al*, 1981).

c) Movement by animals and humans

In the park the winds generally tend to be from east, the dry months being the windiest with August-September showing maximum velocities (Howard & Williams, 1982). Thus it is unlikely that mimosa seed have spread from the western end of the park to the eastern end through wind dispersal.

The role of grazing animals in promoting plant invasions has been widely recognised (Wilson et al, 1991). It is considered that another big factor that has contributed to the spread of mimosa is through transport by animals especially the Kafue Lechwe. Kafue Lechwe, a semi aquatic antelope is found in the floodplain grassland mostly near the fringes of the lagoon where there is abundant grass. The movement of the animal is marked by seasonal fluctuation related to the marked flooding cycle of the Flats. This forces the Lechwe herds to annual cycle of movements and changes in population density related to the availability of grazing. When the flood begins to rise with the onset of rains, the male and the female herds starts migrating from the lower lying areas (Sheppe & Osborne, 1971).

The seed pods of mimosa are covered with bristles that enable them to adhere to these animals and this greatly helps to transport the seeds to far off places. Studies conducted by Lonsdale and Abrecht (1988) in Australian wetlands reveal that many of the outbreaks is due to the movement of vehicles and large mammals. These factors can be responsible for outbreaks up to 80kms away from the large stands of *Mimosa pigra.* Water birds can also be responsible for the dispersal of the seeds to some of the remote sites.

5.4. Ecology of the invasive

Mimosa pigra was reported in the Park by Anon as early as 1958 in the FAO publications of Ecology of the Kafue River Basins, Volume III. As mentioned earlier it has shown up as sings to be an invasive only in the 1990s which means that over 40 years though it has been spreading it did not appear to be invading the area. There are various factors contributing to the explosion of mimosa growth after this period but from ecological point of view this may be considered as one of the phases of plant invasion by woody aliens.

The plant invasion process for any invasive occurs in three phases: Introduction, colonization and naturalization (Groves 1986). Although some invasive species experiences rapid population growth, most of the invasives have a long lag time between the initial introduction and subsequent population growth (Dayton, 1971). Investigation of the population dynamics and ecology of mimosa invasion is yet another study and is beyond the scope of this research. It is interesting to examine whether a change in the natural flooding regime is only phenomenon to be blamed for the rapid colonisation of the species or whether it is the inherent characteristic of the invasive to explode into the area after passing the initial lag phase. The probable reason might be that after the introduction and initial lag phase of 40 years was over it switched on to the next phase of colonising the area where it could take advantage of the disturbances caused due to the alteration of the natural flooding regime. A description of the mechanism of the invasion by the invasive shrub into the area from an ecological point of view is provided in appendix 4.

5.5. Analysis of Markov model

The next objective of this study was to examine if a stochastic modelling process like Markov analysis could help in predicting the expansion of *Mimosa pigra* in future. As mentioned in section 1.4 in pg 11 for predicting a land cover change in future with this method the phenomenon under consideration should fulfill the assumptions of markov chain analysis. So the first step towards this was to prove that if the land cover changes between any two years are dependent or not and if they are whether the changes that had occurred between the two decades are markovian or not. For this it was necessary to prove that the land cover changes between any two years are dependent. This is because the first assumption of markov chain is that the prediction of land cover to the future depends only in state of the preceding land cover. Hence its necessary to prove the dependency of any two land cover images. The results of Karl Pearsons test for independence showed a very high value for all the land cover maps of 1984-94, 1994-2005 and 1984-2005 thus proving that there is very high dependency between them. Therefore in all the three cases the null hypothesis of independency was rejected.

The next step was to test for Markovian dependence in order to examine whether the land cover changes between 1984-94 and 1994 -2005 has followed the same pattern and whether these changes recorded could be used to predict the invasion of *Mimosa pigra* into new areas in the future. As mentioned in in section 4.4.2 pg 58 K square tests was performed for the land cover changes between 1984-2005 using the land cover image of 1994 to compute the expected values. It was found that the computed value was much higher than the critical value which leads to the rejection of the null hypothesis that there is markovian dependence. Since it has been proved that the land cover change process at Lochinvar did not follow a markovian pattern the extrapolation to the future may not be reliable.

The test of significance was done for each cover class to prove if there has been statistical difference in the proportions of the various land cover classes. It was found that there was significant difference in all the classes of interest viz grassland, open mimosa and dense mimosa. The next question to be addressed was why markov analysis was not found to be suitable to predict the land cover changes. There are several reasons to this .One is the limitation of the model itself which is discussed in the next section in detail. The second reason is that the changes in land cover during this span of 20 years so abrupt especially during the last decade that a model like markov cannot account for since it violates the basic assumption of markov model.

5.6. Limitations of the model

There are several limitations to this model since it makes some restrictive assumptions. The computations have established that the land cover changes that has occurred in Lochinvar National Park in the past 20 years with respect to mimosa infestation does not follow a uniform pattern of growth hence the prediction to the future with respect to mimosa infested areas are not dependent on that of preceding years. This is evident on comparing the results of transition probabilities of markov transition matrices of 1984-94 and 1994-2005. This can be further proved by the markov conditional probability images depicting the spatial extent of open mimosa and grasslands predicted in 2005 based on the land cover changes in 1984-94.

In this study it was found that on comparison of the predicted and the actual spatial extent of the two classes the prediction by markov analysis highly underestimates the area likely to be infested by *Mimosa pigra* in 2005. This is because according to Markov first order dependence the projection of the future behavior in terms of probabilities depends entirely upon the property of stationarity and the state of the preceding year. Various studies in Australia have revealed that rate of mimosa expansion does not follow a regular pattern every year. In certain years the infestation doubles every year where as other years it remains passive. This means that the phenomenon of mimosa invasion between 1984-2005 (1984-94 and 1994-2005) is not compatible with the Markov first order dependence.

The Markov chain is said to be stationary or homogeneous in time when the transition probabilities depend only on the time interval t, and if the time period at which the process is examined is of no relevance, (Karlin & Taylor, 1975). The simplest way of understanding the concept of stationarity is to cast it in terms of homogeneity in time, or temporal homogeneity. Thus, a Markov process whose probabilities are identical for two periods of elapsed time of the same duration occurring at different points in time is said to be temporally homogeneous (Bell & Hinojosa, 1976). Alternatively, its transition probabilities are said to be constant for any given period of elapsed time whenever the period may occur. For example if we compare the transition probability of the class grassland to open mimosa for the years 1984-94 projected to 2005 and 1994-2005 projected to 2015 we find it to be

4% and 53% respectively. It is evident from this huge difference of predicted transition probabilities between the two decades that the process is not temporally homogenous. A temporally homogeneous process is stationary when the (unconditional) probabilities of the system being in the different states at future points in time are constant (Bell & Hinojosa, 1976). In this research the process of stationarity was not proved by statistical analysis because it was beyond the scope of this study. The problem of determining whether a given phenomenon is a stationary Markov process is not a simple one and involves careful mathematical analysis (Bell & Hinojosa, 1976). Moreover it was evident that the process of land cover change was not markovian hence there was no point in testing whether the process is stationary or not since it has already violated the first assumption of markov

According to this model the land use at any time, given all previous uses at earlier times, depends at most upon the most recent use and not upon any earlier ones. Markov property asserts that at points of change along these paths the earlier land uses do not guide the future use (Bell, 1974). Markov property states that if it is appropriate to regard land cover change as a stochastic random phenomenon, the markov property states that the past land cover change is not a guide to the future land cover if the present land cover is known. This means that if a land is now in use for open mimosa was formerly grassland the probability of its conversion to dense mimosa depends not the slightest upon its earlier use grassland but only on open mimosa. This has been proved wrong when we examine the cross tabulation results, markov matrix and conditional probability images of 1994-2005. We find that in 1984 and 94 the class dense mimosa was not identified but in 2005 this class was identified.

The results prove that the transition to class dense mimosa is contributed from classes grasslands and open mimosa. This may be because the changes that took place during those 10 years were so rapid that markov property could not account for. These models are difficult to accommodate higher order effects. Baker (1989) suggests that these effects can be modeled by redefining the state space so that new states are defined by both present and preceding states. A second order model, for instance, would include m^2 states instead of m states in a first order mode. Similarly when the land cover change was predicted to 2005 we find that according to markov the probability of grasslands to remain as grasslands in 2005 is as high as 81%.and the probability of open mimosa to invade grasslands is only 4%. But it is evident from the classified land cover image of 2005 that this is not true. Hence

This model is based on pure statistical processes and does link directly to any biological mechanism (Lambin, 1994). The result from this study has proved that the wetland ecosystem is highly dynamic. One of the biggest drawback is that influence of exogenous and endogenous variables to the transitions, cannot be incorporated into the model so that land cover change process can be understood (Weng, 2002). As discussed earlier the spread of mimosa depends to a great extent on the pattern of flooding and its extent and other factors such as soil and geomorphology. The markov model does not take into account any of these variables. Thus for such a dynamic environment which involves complex processes the predictive power of the model would not be suitable. Another big drawback of the model that is evident from the results is that spatial dependence of transitions is not accounted for in simple transition model such as Markov chain.

Management of *Mimosa pigra*

Despite the acknowledged potential effects of mimosa invasion on native flora and fauna in Lochinvar National Park very little effort has been put so far to control the expansion of mimosa infested areas. It is clear beyond doubt that *Mimosa pigra* is an enormous problem posing threat to the biologically diverse and unique wetlands. Yet so far there has been no study related to the growth, spread patterns and management of the invasive alien. So far the only major weed control programme was undertaken in 2004 where there was a mechanical removal operation of a stretch of 0.8ha of mimosa infested areas along the fringes of the lagoon. This was done because mimosa was expanding to the roads which interfered with the frequent movement of vehicles of the park management staff and the tourists. If mimosa is introduced to the area, the prevention of spread is the next priority.

Efforts to prevent the spread of the invasive to new areas generally focus on the control of major infestations, but these efforts are generally unsuccessful (Cook *et al.*, 1996). A detailed discussion on the available management options for the control of mimosa within the Park is beyond the scope of this research. Major projects are being undertaken this year through the joint collaboration between the Environmental Council of Zambia, IUCN and Zambian Wildlife authority for the effective control of the spread of the invasive alien. As with most of the invasives the three options available for the preventing the spread of mimosa is through mechanical, chemical or biological control. The Australian Weed Management Committee has come with various control options to tackle the problem of mimosa invasion as shown in table 5.1. Cook *et al* in his study describes that until biocontrol agents have been become more widely established and proven effective in the field, chemical and mechanical control will remain a more effective means for preventing or slowing the spread of *Mimosa pigra* .He emphasizes that the control of satellite outbreaks remain an important part of the integrated control strategy. However in Lochinvar National Park mechanical removal of the plant cannot be considered as a long term sustainable solution taking into account the costs involved and the extraordinary capability of the plant to rapidly spread to new areas.

Type of infestation	Biological	Chemical	Mechanical	Physical
Small (few plants, small area)	Not suitable	Spot spraying by hand with registered herbicide	Not suitable	Hand grubbing (remove roots and burn plants)
Medium (medium density, medium total area)	Release of biological control agents	Spot spraying by hand with registered herbicide	Chaining, rolling, raking or back-ploughing , then burning	Follow up-control of seedlings - could include physical removal
Large (many plants, many ha)	Step1. Release of biological control agents	Step 2 Aerial spraying with registered herbicide	Step 3. Attack with chaining rolling or raking. Use fire to kill any regrowth and break seed dormancy. Go to step 2 if necessary	Follow- up control of seedlings - could include physical removal.

Table5. 1- Control options for *Mimosa pigra*
(Source- www.weeds.crc.org.au)

Taking into consideration the fragile and diverse wetland ecosystem it seems that mechanical and biological control would be the best options available. Recent studies suggest that biological control can be one of the most effective methods for controlling the spread of mimosa. A study from Australia proves that the best results are obtained when the bio control agents are released at the commencement of mimosa control because these agents require along time to be effective. All parts of the plant — the seeds, flowers, leaves, tips, branches and roots — have been targeted with at least one biological control species. So far, 13 agents (insects and fungi) have been released. Four of these species have become effective in controlling mimosa by reducing seed production and the size of the seed bank, and occasionally killing adult plants (CSIRO, 2002). In the long term biocontrol on its own offers the only cost-effective control option for treating very large infestations of mimosa because of the high costs of chemicals, machinery and labour. However, the present biocontrol agents are very slow acting and may provide effective control only after several decades. Studies by Triet T *et al* (2004) in Thailand showed that for heavily infested areas, strategic weed control programs, employing a combination of several techniques each targeting a specific life date of mimosa have been recommended). Another possible approach would be to encourage the use of mimosa biomass by local communities.

In Mekong Delta, mimosa were used as fuel wood. There are also successful experiments on the use of mimosa biomass as mushroom growing medium and to produce foods for goats from young mimosa stems (Triet *et al* ,2004). There remains a tough task ahead for the planners so as to explore the best options available for mimosa control within the park and how to prevent the spread of alien invasive to the remaining valuable wetlands. Various studies conducted in Australia has shown that sowing of competitive pastures have assisted in controlling the immature mimosa stands. However for dense and mature stands this measure might not be suitable because of the lack of light and nutrients.

However in Lochinvar National Park the root cause of the problem has been identified as the artificial flooding regime which has affected the hydrological balance and the vegetation structure favouring the growth of the invasive. If the natural flooding regimes are brought back it might be effective to control the rapid spread of mimosa to a certain extent. As mentioned earlier though mimosa withstands water logging conditions for long period the rate of growth and the seed production is found to slow down to a great extent. But taking into account the current status of widespread distribution of mimosa within the Park and the enormous capability of the plant to invade new areas the question remains whether mimicking the natural flooding alone would solve the problem of mimosa eradication. Moreover if the plant is in its explosive growth phase little can be done to prevent the further spread through the natural flooding regime.

6. Conclusions and Recommendations

6.1. Conclusions

The study demonstrated that using multitemporal datasets from LANDSAT and ASTER it was possible to map the extent of *Mimosa pigra* and observe the patterns of expansion of the invasive alien in Lochinvar National Park, Zambia from 1984-2005. The study helped to answer the following research questions.

Research Question 1: Which of the datasets available enables a better identification of mimosa growing areas?
When compared to LANDSAT and ASTER datasets used for the study, ASTER proves to be better for delineating the mimosa infested areas.

Research Question 2: Which of the image classification methods is optimal for mimosa delineation?
Maximum Likelihood Classification was found to be the optimal method for mimosa delineation

Research Question 3: What is the optimal number of land cover classes to distinguish mimosa growing areas?
5 land cover classes were required for clearly distinguishing the mimosa infested areas. They are Water, Grasslands, Open mimosa, Shrubs and Dense Mimosa

Research Question 4: What are the areas statistics of each land cover classes identified?

The area statistics of each land cover class from 1984 -2005 is as given below

Classes/yr	1984(ha)	1994(ha)	2005(ha)
Water	5244.2	5391.9	5304.3
Grassland	5552.6	5357.7	2295
Open Mimosa	0	47.2	2644.5
Burned areas	3455.9	3455.9	3455.9
Shrubs	0	0	360.6
Dense mimosa	0	0	192.3

Research Question 5: What are the reasons of mimosa expansion in the study area?

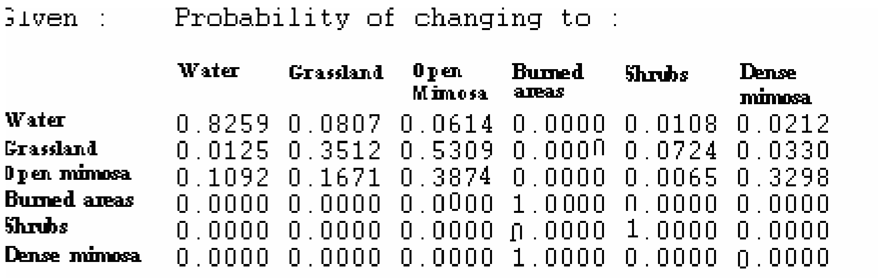
Explosion of *Mimosa pigra* in the park cannot be attributed to a single factor. The most evident reason is that changes in the natural flooding regime after the construction of the Ithezi- tezhi and the Kafue Gorge dams has altered the hydrological balance of the area that resulted in the disturbance of growth of natural vegetation .This along with the other factors like geomorphology of the area, overgrazing and movement of Lechwe may have also contributed to the spread of mimosa to far off places within the Park. Taking into account the dynamics of the invasive woody alien it can be concluded that after the lag phase since its introduction before 1950 the plant has taken advantage of the disturbances within the area that help it to colonise the Park.

Research Question 6: What are the management priorities in Lochinvar National Park and what are the available options for controlling mimosa proliferation in the study area?

Various studies have shown that efforts to prevent the spread of the invasive to new areas generally focus on the control of major infestations, but these efforts are generally unsuccessful. Since the root cause of the problem has been identified as the artificial flooding regime restoration of the natural flooding conditions might help in preventing the rapid spread of the invasive to a certain extent. However considering the current status of widespread distribution of *Mimosa pigra* within the park and the enormous capability of the plant to expand to new areas other options should be considered to tackle the infestation effectively. An integrated management approach would be most effective as physical, chemical or biological control alone cannot control the infestations although combination of these techniques may show promising results. Other management options like sowing of competitive pastures, encouragement of use of mimosa biomass for fuel wood can also be taken into consideration. The characteristic of the infestation, density, location and availability of resources will determine the most appropriate course of control that should be adopted. A detailed study would be required to predict what combination of management strategies will be most effective, what consequences management will have on weed populations and their ability to recover, and how other components of the ecosystem respond.

Research Question 7: What are the transition probabilities of one land cover class to change to the other in the future?

The transition probability of one land cover class to change to the other as predicted by the Markov analysis projected to 2015 is given below



```
Given :     Probability of changing to :

               Water   Grassland  Open     Burned   Shrubs   Dense
                                  Mimosa   areas             mimosa
Water          0.8259  0.0807     0.0614   0.0000   0.0108   0.0212
Grassland      0.0125  0.3512     0.5309   0.0000   0.0724   0.0330
Open mimosa    0.1092  0.1671     0.3874   0.0000   0.0065   0.3298
Burned areas   0.0000  0.0000     0.0000   1.0000   0.0000   0.0000
Shrubs         0.0000  0.0000     0.0000   0.0000   1.0000   0.0000
Dense mimosa   0.0000  0.0000     0.0000   1.0000   0.0000   0.0000
```

Research Question 8: What is the overall transition probability of the various land cover classes of the region to a mimosa affected area?

The above matrix shows the probability of once class to change to the other class over the next 10 years. For the classes of interest water, grasslands, open mimosa and dense mimosa we find that the probability of water to change to class open mimosa and dense mimosa is 6% and 2% respectively. The probability of grasslands to remain as grasslands in the next 10 years is only 35% but the probability to change to open mimosa and dense mimosa as high as 53% and3 % respectively. Similarly for the class open mimosa the probability to remain in the same class after 10 years is 38% and the probability to change to class dense mimosa is 32%.and for class dense mimosa the probability to remain in the same class is 100%.

6.2. Recommendations

This study has proved that there is ample scope for further research into the matter. The following suggestions can be taken into account

A) A detailed study should be done to analyse how the flooding regime has actually changed within the Park since the construction of the Ithezi –tezhi and the Kafue Gorge dams. Though it has been stated that the flooding patterns have changed there is lack of data regarding what was the extent of flooded area before and after the construction of dams, how has it changed, what is the rate of flow of water, depth of flooding and direction of flooding. Satellite imagery such as NOAA/AVHRR and Radar can be promising tools to analyse the spatial extent and the temporal pattern of flooding within the Park.

B) Further studies should be conducted relating to the change of vegetation patterns within the Park in response to the hydrological imbalances created after the construction of the Ithezi tezhi and Kafue Gorge dam. There is lack of information regarding the quality of grasslands and the grazing pattern of lechwe during the pre dam and post dam periods. This will provide an insight of how exactly the overall change in the vegetation structure and grazing patterns has favoured the growth of the invasive alien.

C) Further studies can take into consideration whether Markov chain can be used for the prediction of species that do not expand as rapidly as in case of *Mimosa pigra*. Studies by Gennet (personal communication, 2007) shows that shrubs have been spreading the park over the years but at a much slower rate. Markov chain may prove to be a useful tool to model the spread of steadily growing shrub species and invasives rather than species like mimosa which exhibits an explosive and sporadic growth pattern. This study has only analysed the dependence between the present land cover changes with respect to its previous land cover changes (first order markov process). Higher order markov chains can incorporate a number of time lags in the preceding years which would determine the prediction of the land cover changes to the future. This involves complex mathematical computations but will be helpful to provide better information regarding the probability of transition from one cover class to the other in the future.

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8. Appendices

Appendix 1: (Source Rees 1978 a)

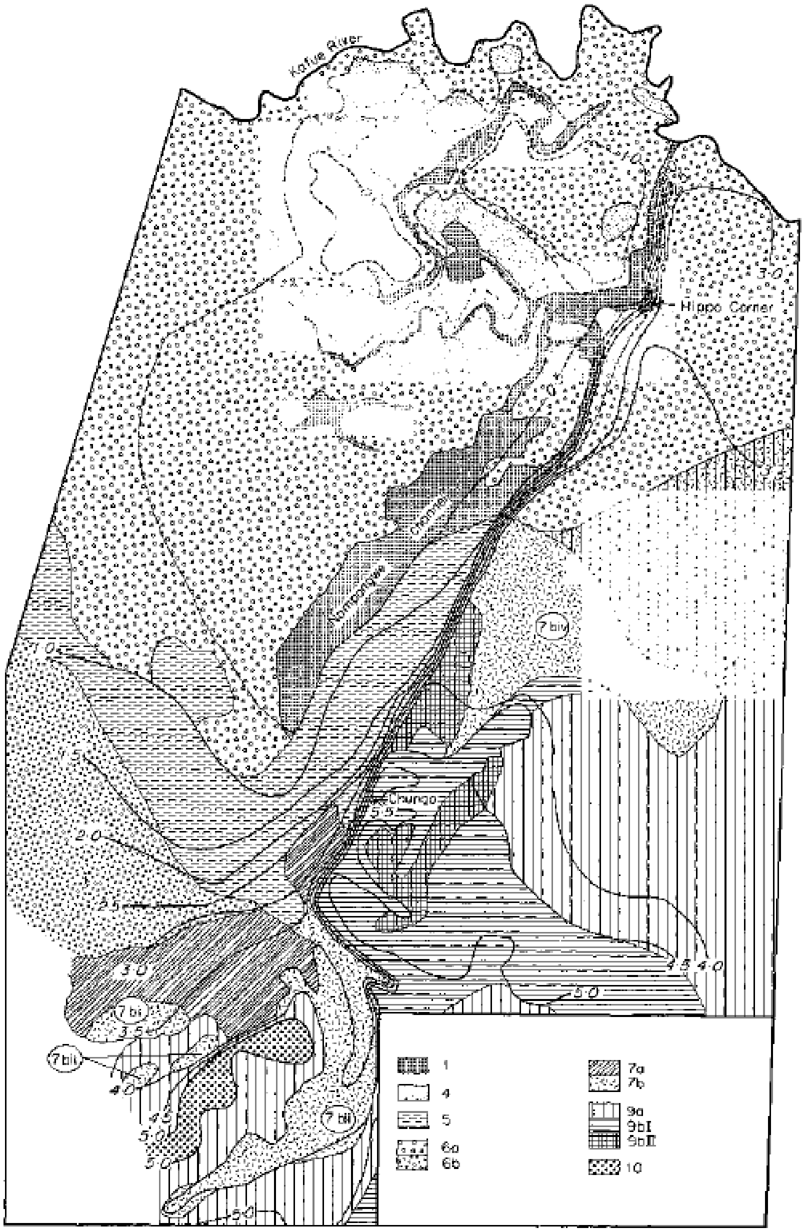

TABLE 1. The topographic units and plant communities of the area utilized by lechwe in Lochinvar National Park, Zambia; the most frequent species in each community are listed

Unit no.	Topographic unit and plant communities	Height (m) above zero water level*	Vegetation	
			Grasses and sedges	Dicotyledons
1	Open water	lower than 0·5		*Utricularia inflexa* *Nymphaea caerulea*
2	River fringe			
	(a) bordering part of the Kafue river only			*Polygonum senegalense*
	(b) all other fringes		*Vossia cuspidata*	
3	River levee			
	(a) bank of Kafue river		*Echinochloa holubii/pyramidalis* *Sorghum verticilliflorum*	*Sesbania sesban*
	(b) all other levees		as above	*Aeschynomene nilotica* *Sesbania microphylla*
4	Old river channels and ox-bows	0·5 and lower	*Echinochloa stagnina* *Vossia cuspidata* *Oryza barthii* *Leersia hexandra*	
5	Lagoon	0·5–2·5	*Sacciolepis africana* *Echinochloa stagnina* dry season: *Cynodon dactylon*	*Aeschynomene fluitans* *Nymphoides indica* *Nymphaea caerulea* *Polygonum limbatum* *Aeschynomene fluitans* *Heliotropium baclei* *Polygonum limbatum*
6	Floodplain grassland			
	(a) Kafue river water	0·5–3·5	*Echinochloa stagnina* *Vossia cuspidata* *Brachiaria rugulosa/latifolia* *Echinochloa holubii/pyramidalis*	dry season: *Ambrosia maritima*
	(b) clear water	1·5–3·0	*Leersia denudata* *Panicum repens* *Eleocharis dulcis*	*Nymphoides indica*

7	Water meadow grassland			
	(a) *Panicum repens* water meadow	3·0–4·0	*Panicum repens*	
	(b) *Acroceras macrum* water meadow	3·5–4·5	*Acroceras macrum*	*Emilia protracta*
			Paspalum orbiculare	*Ipomoea aquatica*
			Sacciolepis africana	*Sida alba*
8	Floodplain fringe		*Vetiveria nigritana*	
9	Termitaria grassland		Grassland between termitaria:	
	(a) *Setaria* grassland	3·5–6·0	*Setaria anceps/sphacelata*	*Hygrophila auriculata* (mainly between 4·5 and 5·0 m)
			Oryza barthii	
			Echinochloa holubii/pyramidalis	*Sida alba*
			Panicum coloratum/subalbidum	
			Brachiaria rugulosa/humidicola	
			Eragrostis inamoena	
			Eulalia geniculata	
	(bI) *Sporobolus* grassland	4·5–6·0	*Sporobolus natalensis*	
			Chloris virgata	
			Digitaria milanjiana	
	(bII) annual grasses	3·75–5·0	*Echinochloa colonum*	*Vernonia glabra/rosenii*
			Brachiaria eruciformis	
			Digitaria ternata	
			Panicum trichonode	
10	Bush-group grassland	5·0	*Oryza barthii*	
			Setaria anceps/sphacelata	
			Echinochloa holubii/pyramidalis	
			Panicum coloratum/subalbidum	
			Digitaria milanjiana	*Hygrophila auriculata*
			Diplachne fusca	
			Eragrostis spp.	
			Brachiaria spp.	
			Panicum spp.	*Ficus burkei* *Albizia harveyi* *Euphorbia candelabrum*

* Zero water level: 973·0 m above N.D.; below this level the floodplain was still inundated in October 1973.

Appendix 2

OBSERVATION POINTS (OBS) TABLE

OBS	X	Y	OBS	X	Y
1	524115	8247034	35	528522	8252006
2	524034	8246919	36	523545	8247453
3	531135	8253716	37	533052	8253490
4	531134	8253716	38	530610	8254818
5	531107	8253679	39	530682	8254896
6	531103	8253688	40	531150	8253171
7	531154	8253716	41	525927	8247833
8	528093	8250253	42	531313	8253220
9	529847	8250619	43	531152	8253125
10	531207	8253646	44	530434	8252456
11	531142	8253777	45	530158	82522410
12	531142	8254309	46	529117	8251553
13	529061	8253547	47	528905	8251230
14	529037	8253744	48	525754	824531
15	529250	8253480	49	522992	8247142
16	530148	8253551	50	528151	8249270
17	530238	8253173	51	527636	8249683
18	525311	8248897	52	521856	8244674
19	525373	8248705	53	525536	8244749
20	525268	8249045	54	522599	8245827
21	525153	8249122	55	519371	8245125
22	526210	8250761	56	519749	8245713
23	526351	8251383	57	519829	8245950
24	526398	8251568	58	519885	8246323
25	526660	8251193	59	519862	8246291
26	527521	8250865	60	519871	8246339
27	529429	8250935	61	519883	8246336
28	530283	8251938	62	524857	8246279
29	530799	8252274	63	519946	8246528
30	530097	8253310	64	519967	8246484
31	528226	8251197	65	519983	8246474

32	528069	8251197	66	519912	8246115
33	527496	8250828	67	519950	8246098
34	526685	8251389	68	519853	8245919
OBS	**X**	**Y**	**OBS**	**X**	**Y**
69	521528	8245702	105	526928	8241272
70	524822	8248290	106	526989	8251893
71	524728	8248208	107	527485	8252456
72	524939	8248368	108	527803	8252896
73	525191	8249297	109	527867	8252995
74	526030	8250703	110	527927	8253106
75	519470	8248350	111	528087	8253388
76	526717	8252122	112	528228	8253601
77	526685	8252131	113	524477	8244069
78	526683	8252121	114	528376	8253842
79	526716	8252192	115	528518	8254064
80	526738	8252323	116	528776	8254291
81	526760	8252396	117	528714	8254320
82	526759	8252373	118	528790	8254351
83	526758	8252350	119	528837	8254356
84	526749	8252334	120	528844	8254359
85	526709	8252326	121	528994	8254238
86	526814	8252090	122	529059	8254478
87	524720	8247799	123	528360	8253846
88	524363	8247210	124	527925	8253117
89	523949	824607	125	523331	8244832
90	523846	8245834	126	523331	8245039
91	520153	8245730	127	523331	8244640
92	520372	8245915	128	529712	8253532
93	520311	8245937	129	529736	8253318
94	520286	8245941	130	529736	8253532
95	520165	8245971	131	530216	8253367
96	520120	8245709	132	530148	8253551
97	520164	8245329	133	530238	8253173
98	520177	8245286	134	529061	8253547
99	520128	8245146	135	529037	8253744
100	519761	8245066	136	525311	8248897

101	519748	8244312	137	525373	8248705
102	526585	8251303	138	525268	8249045
103	526648	8251444	139	530306	8255032
104	526777	8251637	140	530307	8255214
OBS	**X**	**Y**			
141	521556	8246047			
142	521599	8245646			
143	519671	8250337			
144	520196	8249242			
145	520301	8243902			
146	520781	8244096			
147	525413	8249168			
148	525388	8249355			
149	525307	8249005			
150	525603	8249882			
151	525604	8250084			
152	525604	8249681			
153	523406	8246831			
154	523993	8247867			
155	530306	8254814			
156	519401	8247097			

Appendix 3

Name of the Recorder_______ Date Time____strata

Sample plot No	Map scale	Grid reference mark		Crown cover (%)	Location

Intercept interval (cm)	P/A N	P/A S	Intercept interval (cm)	P/A E	P/A -W	Remarks
50			50			
1m			11m			
50			50			
2m			12m			
50			50			
3m			13m			
50			50			
4m			14m			
50			50			
5m			15m			
50			50			
6m			16m			
50			50			
7m			17m			
50			50			
8m			18m			
50			50			
9m			19m			
50			50			
10m			20m			

Appendix 4

ECOLOGY OF INVASION OF *Mimosa pigra*

In this section we describe the process of invasion of *Mimosa pigra* in the area.. There are a number of factors that influence invasion dynamics, including life history traits of native and exotic species, and physical characteristics of the site, such as soil texture and climate. We have a limited understanding of the relative importance of these different processes and environmental conditions on invasion dynamics The populations of introduced species often remain small and localized for long periods of time before they exhibit very rapid expansion. The plant invasion process for any invasive occurs in three phases: Introduction, colonization and naturalization (Groves 1986). While these phases are of human construct, they help us to understand how the invasion process works at different ecological and geographical scales(Platt, 1975). For woody invasives it's only the ability to establish (introduction) and the rate of growth (colonization) in a new environment that are believed to differ from other plants. According to (Crooks & Soule, 1999)this time lag may be due to the nature of population growth and range of expansion, genetic factors to improve fitness or environmental factors related to improving the ecological conditions for the organism. Studies in Australia shows that *Mimosa pigra* had first been reported in 1880 , it was noticed as signs of becoming a weed after 36 years and it was perceived as a problem as invading the are after 90 years. This has also been the case with other invasives like *Chromolaena odorata* which was first noticed in 1955 started as a problem after 7 years and given a pest status after 20years where it started invading the area.

Grime (1979) reports that disturbance might be a major factor favouring plant invasions. Pickett and White (1985) view disturbance more completely as 'any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources or substrate availability or the physical environment'. Disturbance does not always lead to plant invasion, but it may provide a temporary location or "safe site" for a potential invasive species to establish a founding population. Some form of disturbance usually accompanies the success of invasive plant species. For example, Humphries et al. (1991) lists a number of major "environmental" weeds in Australia. He reports that in case of Mimosa pigra expansion in Australia the disturbance that favoured the speed or establishment of the invasive alien the most was water level fluctuations and clearing. Similarly in other invasives such as water hyacinth human interference and nutrient enrichment, buffel grass floods and cattle, mission grass vehicular spread and animal movement contributed to the fast spread of species. In Lochinvar National Park the disturbance that might have affected contributed to the spread of mimosa might be the change of the flooding patterns as discussed in section 4.3a

The second stage of colonisation is characterised by geometric, exponential population growth. Colonization occurs when plants in an introduced, founding (original) population reproduce and then increase sufficiently to become self-perpetuating. This is considered as an explosive growth phase, the invasive often becomes apparent This rate of spread is similar to the population growth rate of an organism in an ideal, resource limitless environment and is therefore believed to be more a function of intrinsic biological characteristics of the species than of its growing environment. During this phase populations of invasive plant species expands by satellite populations that are often isolated from their source. However establishment of a new satellite requires the existence of a vacant site for a dispersing propagules to occupy(Saxena, 1991). Thus, colonization by an invasive species can continue geometrically as both advancing fronts from existing patches and the wide-ranging satellites that arise from them. In the case of Lochinvar National Park the satellite outbreaks might have caused due to the dispersion of seeds by water and movement of animals or vehicles. The establishment of the plant would have taken advantage of the open spaces found between the grasses . For example, (Ghersa *et al.*, 1994) determined that satellite populations of johnsongrass that were uniformly distributed over a previously vacant area occupied that area more quickly than the advancing front of its adjacent source population.

It has been reported that in most invasive woody aliens at some carrying capacity, K, the population approaches a quasi-threshold density where its population growth may remain near one, i.e., stabilize and not expand very quickly (naturalization) The K density occurs when niche occupancy and available resources limit the rate of spread(Williamson, 1996). The conversion to annual grasslands from tussock grasslands in California is an example where biological characteristics play an important role in the invasion process, thus the intrinsic biology of the plant species and the extrinsic nature of the ecosystem are equally important in determining the naturalization of invasive plant species.