Burning wetlands: The influence of fire on wetland vegetation structure and composition

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Submitted in fulfilment of the academic requirements for the degree of Master of Science in

the School of Life Sciences, Faculty of Science and Agriculture,

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Pietermaritzburg

December 2013

DECLARATION 1

This study was undertaken in fulfilment of a Master of Science Degree and represents the original work of the author. Where use has been made of the work of others it is duly acknowledged in both the text and reference section of the dissertation.

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Declaration 2 – Publications

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, in press and published and give details of the contributions of each author to the experimental work and writing of each publication)

Publication 1: Linda Luvuno[1], Reinette (Oonsie) Biggs[2], Donovan Kotze[3]. Zululand Wetlands. In: Regime Shifts Database, www.regimeshifts.org

The work was done by the first author under the guidance and supervision of the second and third author.

Publication 2: Luvuno, L.B.[1], Kirkman, K.P.[1] and Kotze, D.[3], (in preparation), Long-term landscape changes in vegetation structure: a focus on fire as a wetland management tool.

The work was done by the first author under the guidance and supervision of the second author and third author. The work is intended to be submitted to the Wetland Management Journal.

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Abstract

Water is a very important component of the natural world and human survival but water sources (river systems and wetlands) are becoming increasingly degraded and less functional. In particular the increase of woody C_3 species into wetlands is a cause for concern, as they invade wetlands which are predominantly herbaceous. Woody species use more water than herbaceous species and this impacts wetland function. In moister savannahs and grasslands woody species are influenced significantly by fire, and fire is consequently used widely as a means of reducing woody plant density. However, in wetlands there is uncertainty about the effectiveness of fire in combating woody plant encroachment and the general impact of fire.

The Kwambonambi wetlands of South Africa have been recently experiencing an invasion by woody species which are both indigenous and alien. This area was historically herbaceous and experienced frequent natural fire but is now largely under timber plantation and thus fire has been mainly excluded. This has led to a continual increase of woody species into the wetland and has seen a change from mainly herbaceous to a matrix of fern, herbaceous grasses and sedges and an invasion of swamp forest species such as *Macaranga capensis*. This has now affected ecosystem functions and changed fire behaviour in these wetlands. A search through the literature has revealed a lack of studies which investigate the influence of fire on wetland structure and composition. This ambiguity highlights the need for more focused research that will influence management decisions. In order to develop meaningful management strategies, there needs to be a good understanding of the problem and the underlying processes contributing to the degradation and loss of the system you are trying to manage, in this case it is wetlands. This study investigates wetland changes and losses at a small spatial and temporal scale for informing management on the best use of fire on wetlands.

A temporal study (a change detection analysis) reveals that the main drivers of the vegetation structure in this landscape are the land use/land cover change in the form of large scale plantation forestry coupled with fire suppression. 92.4% of the landscape has been altered with the greatest degree of change in this landscape accounted for through the change from grassland and herbaceous wetland (1519ha and 524ha loss respectively) to timber plantation and the spread of indigenous forest indicated by an increase of 70% and 11% increase respectively. The large scale plantation forestry in the landscape has led to the drying of the landscape (which affects the hydrology of the wetlands) and therefore reduces the levels of soil saturation. Simultaneously, plantation forests are fire suppression areas to avoid tree loss. These factors, together with the disturbance of converting wetlands into plantation forest and clear felling (which occurred to **7%/155ha of the wetlands in the study site**), have allowed forest species such as the fern *Staenoclina tenuifolia* and *Macaranga capensis* to invade the wetland areas. Over time, the combination of fire suppression, disturbance and drying encourages the establishment of woody seedlings, turning wetlands into swamp forests/woodlands. This regime shift is more evident in wetlands which were once converted into plantation forest with insufficient woody plant species control to accompany the withdrawal of plantation. The few wetlands which have maintained their herbaceous structure and function are those maintained with fire as a management strategy. A burn experiment shows that fire does have a significant negative effect on tree density in these wetlands- especially previous disturbed wetlands. The recommendation from this study is to remove the forest species out of the wetlands and reintroduce fire (biennial burns) into the management of these wetlands. A better relationship between the forest managers and researchers is recommended to continually co-adapt to any changes occurring in these wetlands.

KeyWords: Wetlands, Fire, Disturbance, Invasions, Land-cover Change, Ecosystem functioning, Management

Acknowledgments

I would like to express my gratitude to the following persons and institutions for the support and knowledge that I received from them during my postgraduate research:

Firstly, Lord Jesus Christ, I wouldn't have gotten through these years without you! Thank You for being my inspiration and driver! Secondly, I extend my gratitude to my dear mother for her love and support during my entire academic career.

I would like to extend a special thank you to my wonderful supervisors, Prof Kirkman and Dr Kotze! Gentlemen, each of you challenged me in a different manner and I have learned so much from you both! Thank you for all your help and encouragement! You are rock stars! Thank you to the rest of my supervision team who played integral roles in this research.

Es, my wonderful friend, for all those weeks spent in the forest, the tantrums we had to endure, operation pot and infamous Tai green curry-thank you! You were my rock that year, truly heaven sent! Mampo and Noks, for the countless hours you had to listen to my research frustrations and encouragement, thank you! Vic, thank you for the time you afforded me bothering you, for challenging me to always push myself and do the challenging thing over the easier version. Thank you to all my friends and family who were there to listen, support and encourage me through this research, you are all precious to me.

Finally, this project would have not been possible without the Mondi Wetlands Programme! Thank you to each member of the team for your help, support and encouragements! These last three years has seen me grow in many ways and I owe it all to the support, challenges and experience you provided me. I truly appreciate the room I was given to grow and discover my capabilities.

Chapter 1

General Introduction

1.1 Background

Water is essential for the functioning of not only the natural world but the functioning of industry and the agricultural sector (Sylvain, 2002). South Africa is a water scarce country, which contributes to water being a limiting resource for development, and a change in water supply could have major implications in most sectors (Sylvain, 2002). According to Rivers-Moore and Goodman (2010), there is a growing recognition of the threatened status of many South Africa's freshwater wetland systems and species. An altered fire regime is one of the impacts identified by Begg (1989) as threatening several of KwaZulu-Natal's priority wetlands. The 2011 National Spatial Biodiversity Assessment found that 55% and 65% of South Africa's river and wetland ecosystem types respectively, are threatened (critically endangered, endangered or vulnerable) and the threats to these aquatic ecosystems are high (Nel and Driver, 2012).

The word "wetland" is a name given to a variety of ecosystems, ranging from rivers, springs, seeps, fens, marshes, pans and floodplains, to coastal lakes, mangrove swamps and estuaries (Mitsch and Gosselink, 2000). These ecosystems all share water as the common primary driving force. Wetlands are ecosystems defined by the National Water Act as: "land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil" (MacFarlane *et al.*, 2008). Wetlands protect and regulate water resources. According to Mitsch and Gosselink (2000), wetlands act as kidneys of the landscape because they receive water and waste from both natural and human sources, and stabilize water supplies by modulating water flow. Wetlands therefore reduce flood damage, help prevent soil erosion, recharge ground water sources, and remove pollutants from the water (Turner *et al.*, 2003).

Factors that contribute to the vulnerability of wetland systems in Southern Africa include seasonal and inter-annual variations in rainfall (Salinger *et al.*, 2005). Climate change predictions forecast further amplifications in seasonal variations (high run-off through intensified flooding and high evaporation rates due to droughts) and inter-annual variations (Hannah *et al*., 2002), thus putting wetlands under even greater stress. This is particularly concerning as water (level and duration flooding) is the primary driver of wetland systems (Mitsch and Gosselink, 2000). These seasonal and annual variations in rainfall, together with size of wetland, water depth, and water balance are factors that affect a wetland's structure and processes and are therefore very important in system functioning (Turner *et al.*, 2003).

Extreme seasonal variations in rainfall are not the only threat to our freshwater and wetland systems according to climate change predictions. Due to the changes in weather patterns predicted by climate change models, there is a predicted shift of boundaries of South African biomes (Hannah *et al*., 2002; Joubert, 2008). The current predictions suggest an increase of non-herbaceous species (trees and shrubs) into open grasslands and herbaceous dominated areas (Bond and Midgley, 2000; Hannah *et al*., 2002; Woodward, 2002; Bond and Midgley, 2012). The shifts and changes of communities are particularly important to the functioning of wetlands as wetland vegetation currently comprises largely of herbaceous species. The predicted changes and increase in tree and shrub species is hypothesised to be largely due to the steady increase of global carbon dioxide concentrations. This increase of global carbon dioxide leads to increasing susceptibility of herbaceous biomes to invasion by shrubs, savanna tree species and increased invasion by alien shrub and tree species (Hannah *et al*., 2002; Bradley *et al*., 2010; Bond and Midgley, 2012).

Concentrations of carbon dioxide in the atmosphere have varied greatly throughout the earth's history and the appearance and spread of C4 grassland biomes is commonly linked to conditions of low carbon dioxide concentration (Bond *et al.*, 2003b; Bond and Midgley, 2012). Different photosynthetic pathways are thought to be the main reason behind the current spread of shrub and tree species into grassland biomes. Plants fall into three categories, namely C_3, C_4 and Crassulacean acid metabolism (CAM) (Collatz *et al.*, 1998). The most common of these photosynthetic pathways is the C_3, which is characteristic of most shrubs and trees. In South Africa, most herbaceous species, occurring outside the desert, fall into either C_3 (mainly forbs) or C_4 (grasses mainly) (Collatz *et al.*, 1998). With the increase of global carbon dioxide concentrations, C_3 plants are predicted to out-compete C_4 plants, due to the C_3 photosynthetic pathway requiring less energy to carry out photosynthesis. According to Bradley *et al.* (2010), the rising atmospheric carbon dioxide concentration has a direct fertilization effect on C_3 plants by increasing resource availability that will favour shrubs and trees, which include the major invasive plants in South Africa.

Another threat to wetland systems is the spread of alien invasive vegetation species (Sax and Brown, 2000; Richardson and van Wilgen, 2004). Alien invasive species are considered one of the biggest threats to biodiversity as they can reduce native species diversity and native species' geographic ranges to a critical point of extinction (Sax and Brown, 2000; Richardson and van Wilgen, 2004). In many parts of the world, the spread of alien species is considered the most challenging and time-consuming task for conservation managers who have a mandate to control alien species, preventing their impacts and repairing systems damaged by the alien species (Richardson and van Wilgen, 2004). According to MacDougall and Turkington (2005), alien invasive species are more indicators of disturbance than they are drivers of disturbance in ecosystems.

Wetlands are not only invaded by alien invasive species, but also by indigenous woody species (Zedler and Kercher, 2004). This is termed bush or shrub encroachment (Ward, 2005; Angassa and Oba, 2008; Moustakas *et al*., 2010). Ward (2005) defines bush encroachment as the suppression of palatable grasses and herbs by encroaching woody species. Bush encroachment is a worldwide concern for land managers because it adversely affects herbaceous species productivity and abundance. Factors causing bush encroachment are poorly understood (Ward, 2005; Wigley *et al*., 2009). There have been a plethora of studies trying to understand this phenomenon. The first attempt at a general explanation was created by Walters in 1939, namely the two layer hypothesis (Ward *et al*., 2013). One of the potential factors being identified is a change of the fire regime or an infrequent fire frequency (Titshall *et al*., 2000; Bond *et al*., 2003a; Uys *et al*., 2004; Bond and Keeley, 2005; Wiegand *et al*., 2006). The study of bush encroachment has been widely studied in the savanna context (Knoop and Walter, 1985; Belsky and Canham, 1994; Wiegand *et al*., 2006; Kraaij and Ward, 2006; Meyer *et al*., 2007) yet poorly studied in wetland environments, especially in the South African context. In Mitsch and Gosselink (2000), fire is only mentioned on 4 of the 770 pages in the third edition of a book titled "Wetlands". South Africa's most noted books on fire and vegetation, "Fire and Plants" (Bond and van Wilgen, 1996) and the "Ecological effect of fire on South Africa's ecosystems" by (Booysen and Tainton, 1984) do not mention wetlands.

There is certainly a scarcity of fire and wetlands related research, which needs to be addressed.

According to Zedler and Kercher (2004), wetlands seem to be especially vulnerable to plant invasions. This is in part because wetlands are landscape “sinks” that accumulate materials such as excess water, nutrients, sediments, salts, heavy metals, other contaminants, and debris, resulting from both terrestrial and wetland disturbances, all of which facilitate invasions by creating canopy gaps or accelerating the growth of opportunistic plant species (Zedler and Kercher, 2004). Even though approximately 6% of the earth’s land area is wetland, 24% of the world’s most invasive plants are wetland species (Zedler and Kercher, 2004). Furthermore, many wetland invaders form monospecific stands, which alter habitat structure, lower biodiversity, change nutrient cycling and productivity, and modify food webs (Zedler and Rea, 1998). Major effects of invasive species include diminished biodiversity and altered basic ecosystem processes, such as nutrient cycling, hydrologic regimes and fire regimes (Zedler and Rea, 1998; Le Maitre *et al*., 1999; Zedler and Kercher, 2004). Biodiversity and ecosystem processes are interactive; therefore ecosystem processes altered by invasive plants may inhibit native species while favouring selected alien species. This highlights the need for management strategies which will effectively reduce the occurrence of invasive species in wetlands. Fire has frequently been used as a management strategy to reduce tree and shrub densities for both indigenous and exotic invader species (Bond and van Wilgen, 1996; Hoffman and O’Connor, 1999; Titshall *et al*., 2000; Uys *et al*., 2004; Bond and Keeley, 2005; Wiegand *et al*., 2006; Tollope, 2007) but the effect of burning wetlands is not well understood (Watts *et al.*, 2012).

Fire has been taking place naturally for millennia in grasslands, tropical savannas and forests as a landscape disturbance (Bond and van Wilgen, 1996; Bucini and Lambin, 2002; Bond and Keeley, 2005; Tollope, 2007). Similarly, humans have been using fire as a tool to manage these fire prone ecosystems and have used fire to shape biome distribution.

The intermediate disturbance hypothesis states that the highest diversity is achieved through intermediate disturbance (Blair, 1996). The essential elements of the intermediate disturbance hypothesis are that there must be a repeated local disturbance, and disturbance must be frequent enough so that competitive exclusion does not occur over the whole area, yet not so frequent that most species are eliminated (Blair, 1996). Regular fire fits the definition of an intermediate level disturbance and is likely the reason fire is a widely used method of managing bush encroachment and alien invasive species. Despite the recognized importance of fire as an ecological driver, there has been very little research undertaken on the effect of fire on wetland vegetation composition and structure. With growing concern over deteriorating water quality and quantity, both globally and in South Africa, there is a need to better understand the effect of fire on wetland functioning, specifically the effect of fire on wetland vegetation structure.

1.2. Research Gaps

As with grassland and savannas, fire has been taking place naturally for millennia in South African wetlands. These wetlands have also evolved under a regime of periodic fires, yet the effect of burning has not been thoroughly investigated in this ecosystem. According to Smith *et al.* (2001), there have been few studies of the effect of fire on wetland functioning despite wetland burning potentially having wide-ranging environmental consequences.

The few studies done on wetland burning have returned ambiguous results on its effect on vegetation. Those focusing on hydrology as a driver of vegetation type, propose that burning could affect the hydrology of the wetland which will then affect the vegetation of the wetlands. Watts *et al.* (2012) states that burning wetlands with high soil organic carbon produces significant hydrologic consequences such as drying wetlands by affecting the hydroperiod (the duration of flooded or saturated conditions) and this could significantly affect vegetation communities. Both Newman *et al.* (1998) and Watts *et al.* (2012) describe areas where ground fire in wetlands high in organic matter resulted in the lowering of soil elevations by consuming the organic matter which favoured certain species over the others. Contrasting views propose that fire is an efficient strategy to manage the invasion of woody non-wetland species (Kirkman, 1995; Clark and Wilson, 2001), especially when the burn timing is correct (DiTomaso *et al.*, 2006) with no major effect to the soil structure. This ambiguity highlights the need for focused research that will influence management decisions to address the high levels of wetland degradation.

The need for this research is amplified for South African wetlands with a long fire history and which are reliant on fire for maintaining their vegetation structure and composition. Examples of this include the Kwambonambi wetlands, which were selected for studying the impacts of fire on wetlands. According to Henkel *et al*. (1936) the Kwambonambi area experienced regular fires, which was noted to be of great ecological importance in preventing the extensive expansion of forest. The Kwambonambi wetlands are therefore naturally dominated by herbaceous vegetation which is well adapted to regular fires. These wetlands support a rich diversity of herbaceous plant species, including the only known wild population of the critically endangered *Kniphofia leucocephala* (Scott-Shaw, 1999).

According to Henkel *et al*. (1936), forest was generally confined to locations protected from fire in the Kwambonambi area. However, in the last four decades, the area has been subject to very high levels of transformation due to tree plantations, mainly of the exotic *Pinus elliottii* and recently *Eucalyptus grandis,* and human settlements, with profound potential implications for the wetlands in this landscape. According to Helmschrot (2005), the effects induced by large plantations include a variety of both changes in the hydrological system behaviour and ecological changes such as drying out of wetlands and the destruction of natural habitats. Hydrological impacts include increasing transpiration loss by approximately 500mm annually in areas that were historically herbaceous (from 900mm to up to 1400mm annually when afforested) and rainfall interception by losses of up to 12% of the MAP (Dye and Versfeld, 2007). The impacts of the extensive tree plantations in this area would appear to have compounded the effect of reduced fire. The impact land management has on ecosystems has been acknowledged globally as scientists realise the significance of human alteration on ecosystems (Tilman and Lehman, 2001; Francis *et al*., 2005; Folke *et al.*, 2004; Wallington *et al*., 2005; Dye *et al*., 2008; Moore *et al*., 2009). Long-term ecological research has revealed that the legacies of historic land-use activities continue to influence the long-term composition, structure, and function of ecosystems decades and centuries after the activity has ceased (Wallington *et al*., 2005).

The land use change coupled with the subsequent land management in the Kwambonambi area has led to the reduced incidence of fire in this landscape, which is hypothesised to have resulted in extensive encroachment of the herbaceous wetlands by woody plants, notably *Macaranga capensis*, but prior to this study this encroachment had not yet been investigated.

It is important to note that Henkel *et al*. (1936) also revealed that while fires prevent the expansion of forest, they normally are unable to penetrate or burn back the forest, hence the significance of understanding the interaction of fire and plants in these wetlands and initiating a better dialogue between research and land management to better manage altered ecosystems, especially in this rapidly changing landscape.

1.3. Aim and Objectives

1.3.1. Aim:

The aim of this study was to examine the influence of fire on wetland vegetation structure and composition of the Kwambonambi wetlands, South Africa.

1.3.2. Objectives:

- To compile a fire and disturbance history of the Kwambonambi wetlands.
- To identify long term changes in vegetation structure using remote sensing and relate these to fire history.
- To compare the differences in wetland vegetation structure and composition in wetlands with differing fire history.
- To compare the effects of different fire regimes on the occurrence of invasive woody species.

Addressing these objectives will inform management decisions regarding the appropriate use of fire in these wetlands.

Overview of Chapters

Chapters 2 and 3 have been prepared as stand-alone papers. Each chapter has an introduction which may include some of the ideas that have already been discussed in this introduction, resulting in minor repetition.

Chapter 2 is an investigation of the history of the landscape of the Kwambonambi area and the effect that the changes in the landscape have had on the wetland management and the subsequent structure of the wetlands.

Chapter 3 is a vegetation ecology study on the effect of fire on vegetation structure and composition based on a fire experiment conducted in two individual wetlands.

Chapter 4 is a combination of the discussions and conclusions from Chapters 2 and 3, followed by recommendations for encouraging the incorporation of key findings of the study into management practice. Appendices pertaining to the data chapters are attached at the end.

Chapter 2

Long-term landscape changes in vegetation structure: a focus on fire as a wetland management tool.

2.1. Introduction

2.1.1. Background

In light of climate change, the need for conserving biodiversity, and consequently ecosystem services, is becoming increasingly significant (Hannah *et al*., 2002). The need for conserving whole ecosystems and landscapes in order to conserve biodiversity as a whole, as opposed to a single species, has become a focal part of research and conservation strategies (Franklin *et al*., 2002; Slocombe, 1998; Wallington *et al.,* 2005; Moore *et al*., 2009). This is due to large scale conservation having far reaching consequences because this not only provides habitats for biodiversity but also allows the ecosystem to supply the invaluable ecosystem goods and services which humans rely on (Chapin *et al.,* 1998; Slocombe, 1998; Chapin *et al.,* 2000). The biggest threat to biodiversity has been acknowledged as habitat destruction and is currently a focal point of conservation efforts (Chapin *et al*., 2000; Miller and Spoolman, 2009; Foody, 2002; Wallington *et al*., 2005; Rogan *et al*., 2008; Otukei and Blaschke, 2010). Biodiversity is the variability among living organisms; diversity within species, between species and the ecosystems they inhabit. Habitat destruction is any relatively discrete event in time that displaces or removes organisms and opens up space, thus creating opportunity for new individuals or colonies to become established (Leveque and Mounolou, 2003).

The most significant habitat destruction taking place the world over is in the form of land use/cover change. Land cover undergoes both natural and anthropogenic changes. Currently, anthropogenic factors, such as urbanization, mining, intensive agriculture, deforestation and afforestation have become more significant as causes of change to the earth's surface, while natural factors, such as bush encroachment and erosion also play a significant but minor role (Chapin *et al*., 2000; Fanan *et al*., 2011). According to Otukei and Blaschke (2010), land cover change is regarded as the single most important variable of global change affecting ecological systems with an impact on the environment that is equivalent to that associated with climate change. Chapin *et al*. (2000) and Foody (2002) have projected that land-use change will have the largest global impact on biodiversity in this century due to land cover change having significant effects on ecological processes. This concern over land cover change centres around the disruption of once large continuous blocks of habitat into fragmented habitat, primarily by anthropogenic disturbances (Franklin *et al*., 2002). During fragmentation, the total area of original habitat is reduced, the remnants are broken and isolated into "islands" of varying sizes and these remaining fragmented "island" habitats are changed (Malvido, 1998), thus influencing the ecological processes in the remaining habitats (Diaz *et al*., 2006). This is because the functions of an ecosystem such as the regulatory functions and the production functions are greatly dependent on the ecological state of the ecosystem (Müller *et al.,* 2000). According to Diaz *et al*., (2006) the anthropogenic factors that drive land use and land cover change that affect biodiversity indirectly also affect biodiversity-dependent ecosystem processes and services.

In recent decades as land cover changes are becoming a more significant earth alteration variable, there have been a number of studies trying to understand the ecosystem consequences of a changing biodiversity (Chapin *et al*., 1998; Chapin *et al*., 2000; Loreau *et al*., 2001; Tilman and Lehman, 2001; Bunn and Arthington *et al*., 2002). The focus of these studies is on the predictable functional shifts associated with a declining biodiversity as sets of species with particular traits are replaced by other species with different traits (Loreau *et al*., 2001). Species alteration of the availability of limiting resources, the disturbance regime, and the climate can have particularly strong effects on ecosystem processes (Chapin *et al*., 2000), and conversely these environmental constraints dictate the species which are present in a community (Tilman and Lehman, 2001). Such effects are most visible when introduced species alter previous patterns of ecosystem processes (Chapin *et al*., 2000).

Land cover is a primary variable that impacts on and links with many parts of the human and physical environment (Foody, 2002). Land cover dynamics are part of the main interests of environmental monitoring (Rymasheuskaya, 2007). Despite the significance of land cover as an environmental variable, our knowledge of land cover and its dynamics is poor. Understanding the significance of land cover and predicting the effects of land cover change on biodiversity and ecosystem function is particularly limited by the paucity of accurate land cover data (Foody, 2002). Intensive use of natural resources calls for increasingly detailed inventories of its components and an investigation of the changes which took place in the past (Lopez *et al.*, 2001; Kuenzer *et al.*, 2011).

In recent decades, data from remote sensing satellites have become vital in mapping the earth's features, managing natural resources and studying environmental change (Rymasheuskaya, 2007; Fanan *et al*., 2011; Rocchini *et al*., 2012). Remote sensing, mainly using satellite imagery and Geographic Information Systems (GIS) are now providing the required tools for advanced ecosystem management (Foody, 2002; Fanan *et al*., 2011; Haas *et al*., 2011; Kuenzer *et al.*, 2011; Mutanga *et al*., 2012; Rocchini *et al*., 2012). Remote sensing has become a critical tool in mapping, understanding the context and in predicting the effect of alteration of ecosystems (Foody, 2002; Fanan *et al*., 2011; Kuenzer *et al.*, 2011).

2.1.2. Research Gaps

The landscape of the Kwambonambi area has changed remarkably over the last 8 decades. This change has been largely due to large-scale commercial forestry development in the area since the late 1930s. The effects induced by large plantations on landscape dynamics are numerous (Helmschrot, 2005), and include an array of changes in the hydrological system such as runoff reduction, interception losses and water table fluctuation as well as ecological changes such as drying out of wetlands, biodiversity reduction and destruction of natural habitats (Dye *et al*., 2008; Helmschrot, 2005). A quantified description of the impacts of the afforestation on wetlands in this region is thus required.

The change of the natural disturbance regime is the most concerning and noticeable change in this area. Due to the changes in the landscape, this area has changed from an area that experienced fire as part of its natural disturbance regime to a regime of fire exclusion. These regime shifts, and thus the shifts in functioning of ecosystems are significant, as the resulting ecosystem effectively does not supply some ecosystem goods and services or supplies them to a lesser degree (Troell *et al*., 2005). According to Tilman and Lehman (2001), the two extremes of fire management, the suppression and active increase of fire as a management tool has changed regional fire frequency, and has become a major force structuring communities and ecosystems. This impact on natural ecosystems by land management has recently been acknowledged as significant as scientists realise the significance of human alteration on ecosystems and their subsequent management (Tilman and Lehman, 2001;

Francis *et al*., 2005; Wallington *et al*., 2005; Dye *et al*., 2008; Moore *et al*., 2009). Moore *et al*. (2009) reviewed the current ecological thinking of biodiversity conservation and revealed the diversity of views from ecologists on ecological concepts that have management implications. Ecosystems are complex, dynamic and unpredictable which makes managing land for multipurpose use a complex endeavour (Wallington *et al*., 2005; Moore *et al*., 2009), thus encouraging the need to evaluate the effectiveness of the current land management on ecosystems.

Long-term ecological research has revealed that the legacies of historic land-use activities continue to influence the long-term composition, structure, and function of ecosystems for decades and centuries after the activity has ceased (Wallington *et al*., 2005). This implies that present ecosystem conditions must be understood in the context that incorporates past land use and natural disturbance. Conservation efforts therefore should be focused on altered ecosystems and the dialogue between research and land management needs to be improved to better manage altered ecosystems (Wallington *et al*., 2005; Moore *et al*., 2009). This need for contextual and amalgamated understanding of ecosystems suggests that research should be done at multiple temporal and spatial scales (Chokkalingam *et al*., 2005; Wallington *et al*., 2005; Moore *et al*., 2009).

This study uses remote sensing to accomplish the need for multi-temporal understanding of the Kwambonambi area, with a specific focus on the changes in the wetlands which are considered vulnerable by the South African National Biodiversity Institute. This specific focus on wetlands is due to the concern over the effects plantations have on the hydrological system of the area and plantation management through fire suppression as local drivers of vegetation structural changes. These structural changes occur through the invasion of woody species into the wetlands where fire, as a natural disturbance regime, is thought to play a significant role in maintaining their structure and composition.

This concern is amplified by the global prevalence of bush encroachment (the increase of woody plants into herbaceous dominated systems) and its many drivers, one of which is the increase of the global concentration of carbon dioxide in the atmosphere, which contributes to a faster growth period in trees (Bond & Midgley, 2000; Hoffmann *et al*., 2000; Roques *et al*., 2001; Bond *et al*., 2003b; Wiegand *et al*., 2006; Kraaij and Ward, 2006; Britz and Ward, 2007; Wigley *et al*., 2009). The need for this study arises from a paucity of relevant research needed to support the management of wetlands in this altered, rapidly changing ecosystem supporting the critically endangered *Kniphofia leucocephala*, hence the need for a contextual understanding of this ecosystem. There is a need to quantify the effects plantations have on the ecosystem, the consequence of fire suppression on the wetlands and to evaluate the effectiveness of the land management on ecosystem.

2.1.3 Aims and Objectives

2.1.3.1 Aim

The aim of this study is to investigate landscape scale changes in vegetation structure in the Kwambonambi, Zululand, area of South Africa, between 1937 and 2009 with a focus on fire as a wetland management tool.

2.1.3.2 Objectives

To meet the aim of the study, the following objectives have been set:

- To evaluate the long term changes in vegetation structure using remote sensing.
- To compare the differences in wetland vegetation structure in wetlands with differing fire history.
- To compare the effects of different fire regimes on the occurrence of invasive woody species.

2.2 Methods and materials

2.2.1 Site description

The study site, which covers 2 230 ha, is located in Kwambonambi in the eastern coast of KwaZulu-Natal Province, South Africa. The study was conducted between longitudes 32°9'E and 32°13'E and latitudes 28°35'S and 28°39'S (Fig. 2.1). This area falls in the Maputaland coastal plain which is characterised by coastal sandy grasslands rich in geoxylic suffrutices, dwarf shrubs, small trees and very rich herbaceous flora (Mucina and Rutherford, 2006). The study area was historically characterised by many inter-dune depression wetlands and hygrophilous grassland neighboured by wooded grassland (Henkel *et al.*, 1939; Mucina and Rutherford, 2006). Currently, most of this area is under timber plantations, predominantly *Eucalyptus* species.

[1]Rain falls all year but predominantly in the spring-summer months of October to March. The mean annual rainfall is 1378mm and the potential evapo-transpiration is 1772mm (Little and Rolando, 2001; [1]South African Weather Service data, 2012). This area experiences high humidity levels in summer, with winter being more moderate. Temperatures are never extreme due to the moderating maritime influence, and the annual temperature average is 25°C. The altitude ranges between 20-120 m above sea level with the variation due to the changes in dune altitude.

The geology of the area is the Kwambonambi formation which belongs to the Cenozoic unconsolidated sediments group (Le Maitre *et al.*, 1999). The soil is mainly fine sand, with various levels of organic matter and clay mineral content. This area is situated above a coastal primary aquifer which is generally recharged through direct rainfall (Kelbe and Germishuyse, 2010) which helps maintain the wetlands in the region.

[1] (South African Weather Service data, 2012: Unpublished data)

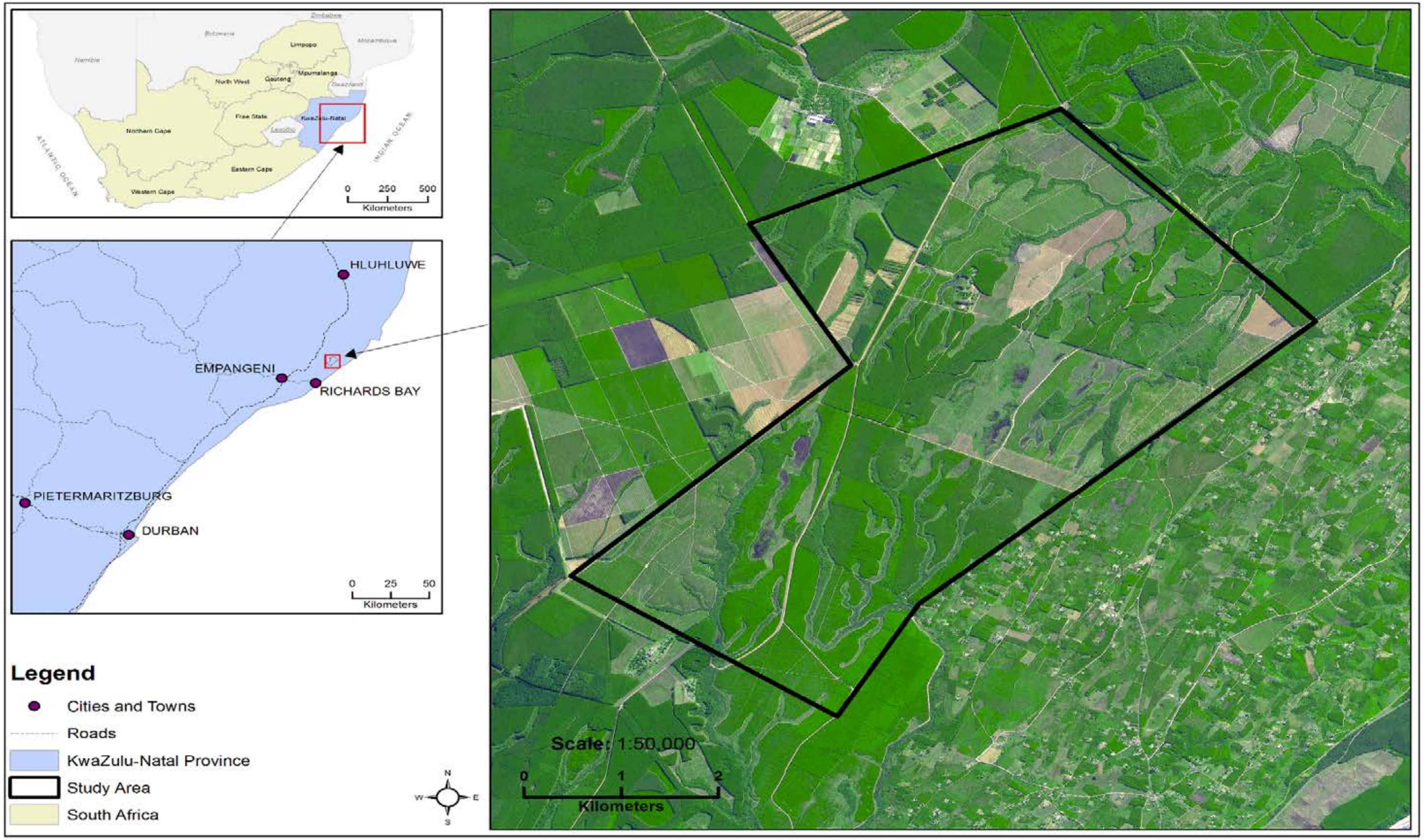


Figure 2.1: Study site location: Kwambonambi.

2.2.2 Methods

A change detection analysis was conducted to analyse and detect land cover change using remotely sensed data. There are various methods of performing a change detection analysis (Mas, 1999; Odindi *et al*., 2011). The quality of the analysis is often determined by the spectral and spatio-temporal limitations, and therefore it is important to select the appropriate techniques (Fuller *et al*., 2003; Odindi *et al*., 2011). Post classification technique is the choice of most studies (Mas, 1999; Chen, 2002; Fuller *et al*., 2003; Li and Zhao, 2003; Rymasheuskaya, 2007; Odindi *et al*., 2011). The post classification technique analyses the change in classified multi-temporal land cover maps and was the choice for this study. Mas (1999) compared a variety of techniques where post-classification was found to be the most accurate technique and it presented the advantage of indicating and quantifying the nature of the changes (Fuller *et al*., 2003).

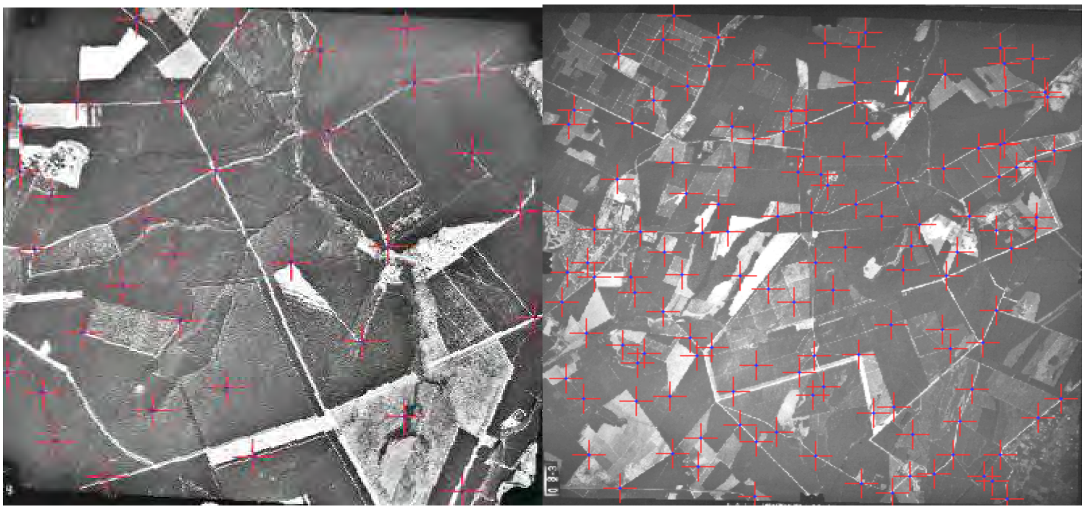
Multi-temporal imagery from three generations, from the late 1930s to the most recent imagery, was chosen for the purpose of this analysis. Satellite imagery cannot be used as it was only available from the 1970s. Three sets of aerial photographs were obtained from the University of KwaZulu-Natal's Cartographic Unit in the Geography Department, allowing for the detection of land cover changes that have occurred over the set period. The images chosen were from 1937, 1970 and 2009. These particular dates were chosen to include data pre-existing the large scale afforestation that has occurred in the area.

Pre-processing of the dataset consists of three essential procedures: projection and geo-rectification of aerial photographs, and digitization of various land cover types from these historical aerial photographs. All these procedures were done in ArcGIS 10 (Environmental Systems Research Institute, California, United States of America). The scanned historic aerial photographs do not contain spatial reference information, thus the images required projection and geo-rectification. The process of projection is attaching a co-ordinate system to the images for the purpose of viewing the images with other geographic data to be analysed and geo-rectification is the process of positioning images into their correct geographic locations thereby correcting any geometric distortions. In order to be able to overlay these images with other remotely sensed images or topographic maps, geometric correction in the form of geo-rectification is necessary (Rocchini *et al*., 2013). This necessity arises from the need of accurate metric calculations on a landscape being sensitive to geometric distortions (Rocchini and Di Rita, 2005; Rocchini *et al*., 2012). Accurate metric calculations are required for realistic multi-temporal studies. The process of geo-rectifying raster data requires the dataset to be added to the software along with rectified data. During this process, identifiable ground control points (GCPs) were selected on the rectified data and matched to the same points on the un-rectified data. A minimum of 25 ground control points which were evenly dispersed within each image were used, on images which were at a scale of 1: 20 000 or less (Fig. 2.2) The number of GCPs used during geo-rectification is considered to be an important factor that influences geo-rectification accuracy (Rocchini and Di Rita, 2005; Hughes *et al*., 2006). The GCPs are used to build a polynomial transformation that will convert the images from their existing location to the spatially correct location. This precision is localized to the pixels closest to the control points, hence the importance of including as many evenly distributed control points as possible to increase the overall accuracy of the geo-rectification. The spline transformation algorithm, which produced the best geo-rectification accuracy, was used.

Different land cover types were then identified from the imagery and the land cover types significant to this study were chosen. Bare soil patches for example were not significant to this study as they were small in extent and the main interest of this study was large scale change as well as changes to the wetlands in the study site. These major land cover types in the study area span the whole study period included in this research. The land cover types were then manually digitized from the newly geo-rectified imagery. The land cover classes that were digitized were: Herbaceous Wetland, Grassland, Indigenous Forest (Swamp forest/woodland consisting of indigenous species), Plantation, Human-Settlement, Herbaceous-Fern mix (a mixture of herbaceous species and various fern species) and Herbaceous-Fern-Tree mix.

Following this process, vector maps were created consisting of the major land cover classes. These vector maps were then converted into TIFF raster formats and further imported into IDRISI raster format for the change detection analysis. There are a number of methods available to perform a change detection analysis, the Land Change Modeller (LCM) for Ecological Sustainability embedded in IDRISI 15.0 Andes version (Clark Labs, Worcester, United States of America) was used for this study. The LCM compares land cover classes of a map of an early period with a map from a later period. The products of the LCM are change maps depicting which land cover class changed and to which class, graphs of gains and losses of area between the different periods and graphs depicting which land cover classes were contributors to certain changes in land cover.

The product of this analysis was then related back to the fire history of the area. The fire history record was compiled from the forest records and interviews with forest managers, both past and present. Due to the reliance on forest managers' memory, a specific fire history was not possible. Fire history was categorized between: Never been burnt, burnt once, and burnt more than once in 25 years of current forest management. Sample wetlands with a known fire history were chosen and classified using Edwards Classification System (Edwards, 1983) for a broad-scale structural classification of vegetation to compare structure against their fire history.



a). b).

Figure 2.2: Examples of the use of ground control points (GCPs) in the geo-rectification process. a). 34 GCPs used on a 1:25 000 image b). 135 GCPs on a 1: 50 000 image.

2.3 Results

2.3.1 Change analysis using Land Change Modeller (LCM)

Results from the land cover change analysis revealed great changes in this landscape. Comparisons were done for land cover changes between 1937 and 1970, between 1970 and 2009 and the overall changes between these periods from 1937 to 2009. The greatest observed change is the drastic decline in grasslands from 1556ha to 37ha and increase in plantations from 25ha to 1598ha respectively (Table 2. 1 and Fig. 2.4) from 1937 to 2009. It is apparent there is an overall change from an herbaceous ecosystem with mostly herbaceous grass and wetland species to a wooded ecosystem with plantation tree species and indigenous forest (Fig 2.3). Overall, this ecosystem seems to have lost most of its diversity with 2123ha of habitat mainly occupied by herbaceous species being reduced to 80ha (Table 2.1) and replaced with 1942ha of 1-2 tree species of plantation trees (1598ha) and indigenous forest (344ha) occupying most of the area.

Focusing on the changes to the herbaceous wetlands, Fig 2.5 and Table 2.2, the change to plantation and indigenous forest has caused the significant changes to this land-cover class. Most of this change occurred within the period of 1937 and 1970 with 80% of the wetlands in this landscape being converted to plantation. The changes between 1970 and 2009 are of a lesser extent but still significant due to the considerable cumulative changes over the whole period. The major change in this period is the increase of indigenous forest and the emergence of the mixed fern and tree classes. These changes are largely due to the clear-felling of plantation from historically herbaceous areas, an indication that when plantations are clear-felled, the vegetation does not revert to its original composition and structure.

Table 2.1: Changes in land use and land cover classes in the study site during the study period. Total area of study site is 2242

Land-cover Classes	Area (ha)			Percentage change of total area (%)		
	1937	1970	2009	1937-1970	1970-2009	1937-2009
Grassland	1556	198	37	-60.8	-7.2	-67.7
Herbaceous Wetland	567	130	43	-19.5	-3.9	-23.4
Indigenous Forest	94	132	344	1.7	9.4	11.1
Human Settlement	0	32	10	1.4	-1.0	-0.4
Plantation	25	1753	1598	70.8	-6.9	70.2
Herbaceous, Fern Mix	0	0	88	0	3.9	3.9
Herbaceous, Fern, Tree Mix	0	0	122	0	5.4	5.4

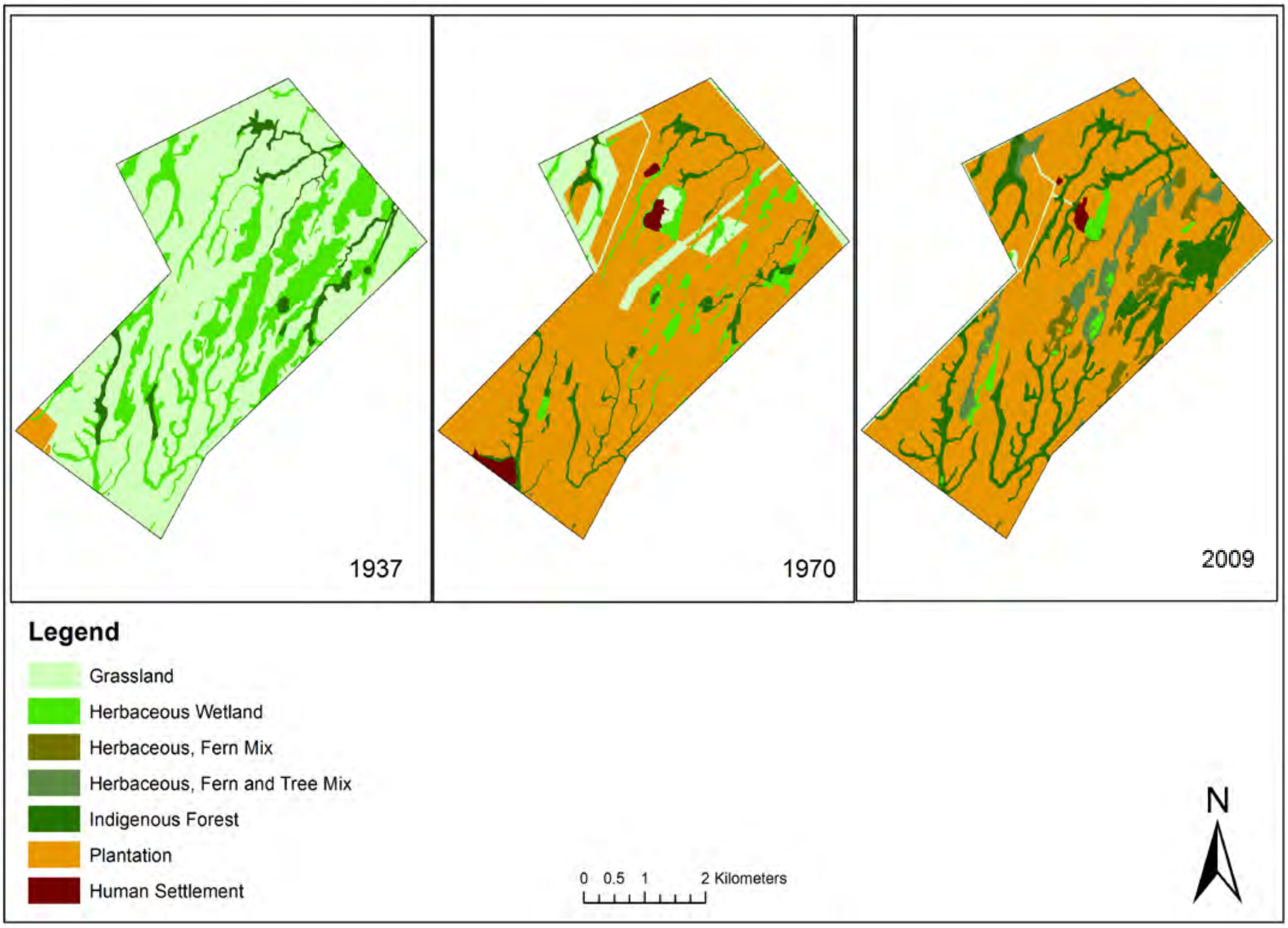


Figure 2.3: Digitized land cover maps of the study site.

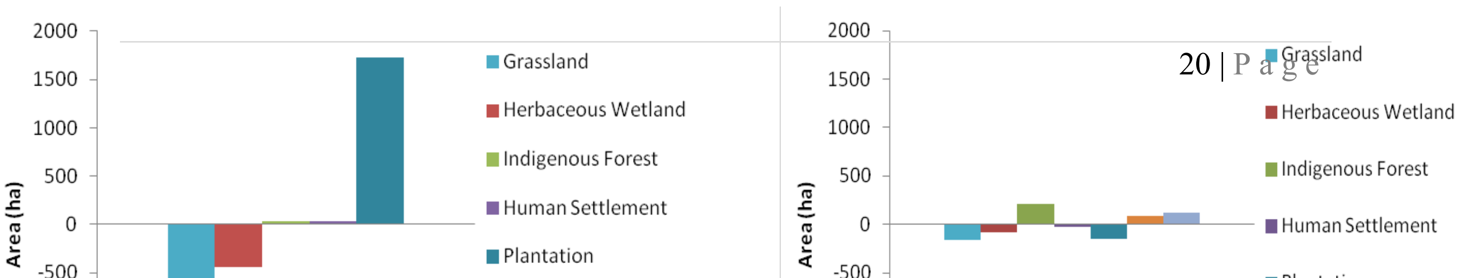


Figure 2.4: Changes in area of the different land-cover classes between 1937, 1970 and 2009.

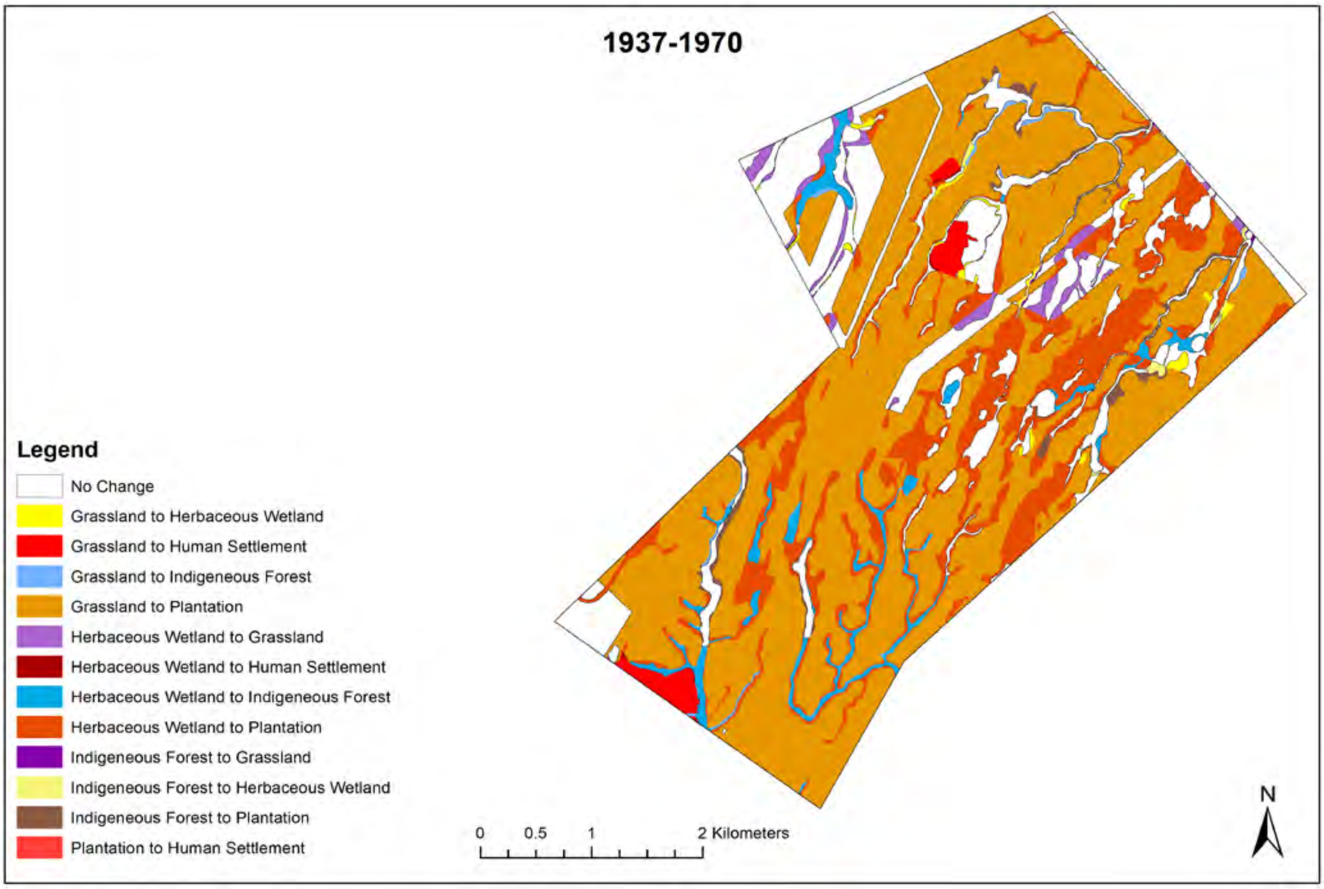


Figure 2.5: Land cover change maps highlighting changes from one land cover to another (1937, 1970 and 2009).

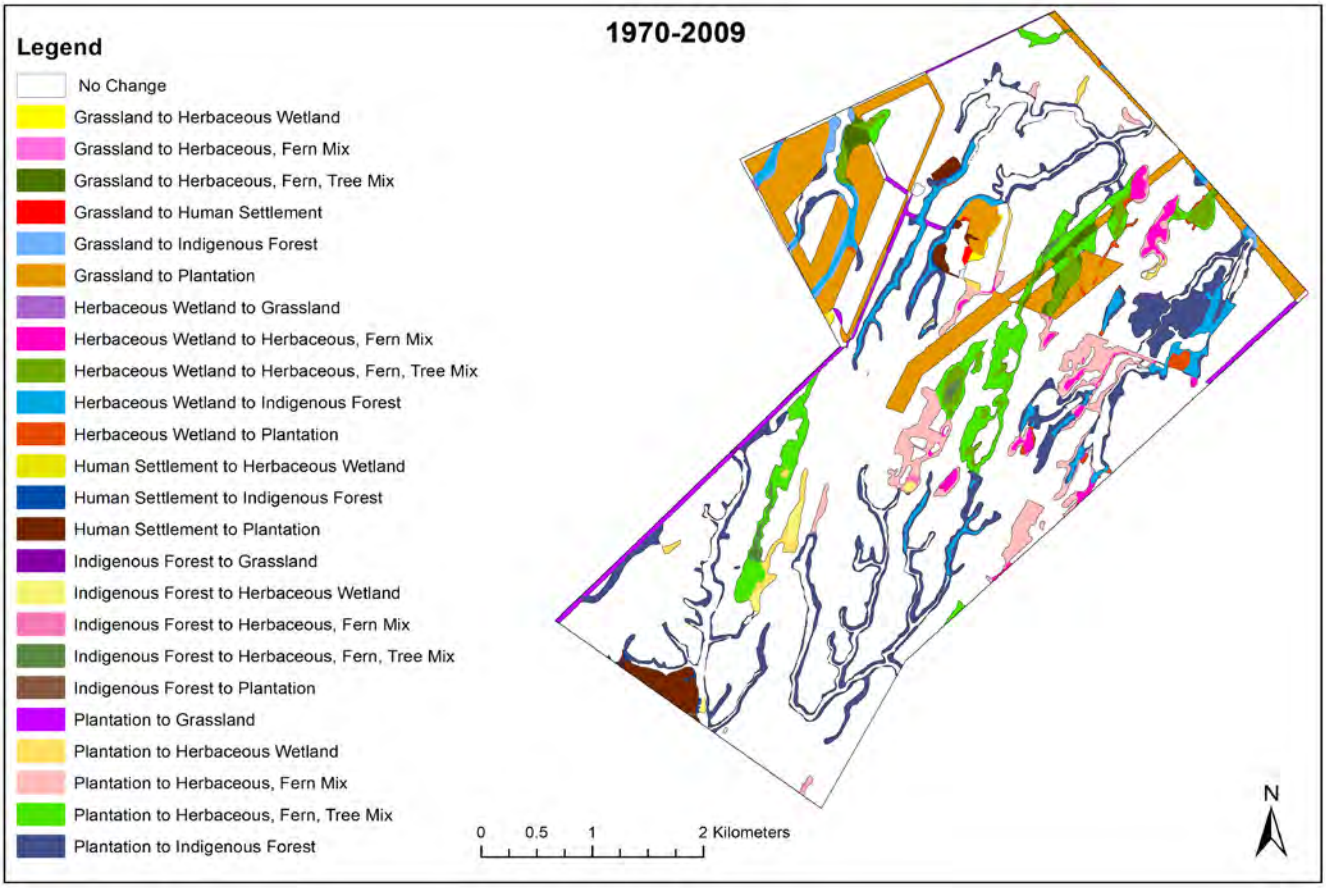


Figure 2.6: Land cover change maps highlighting changes from one land cover to another (1937, 1970 and 2009) continued.

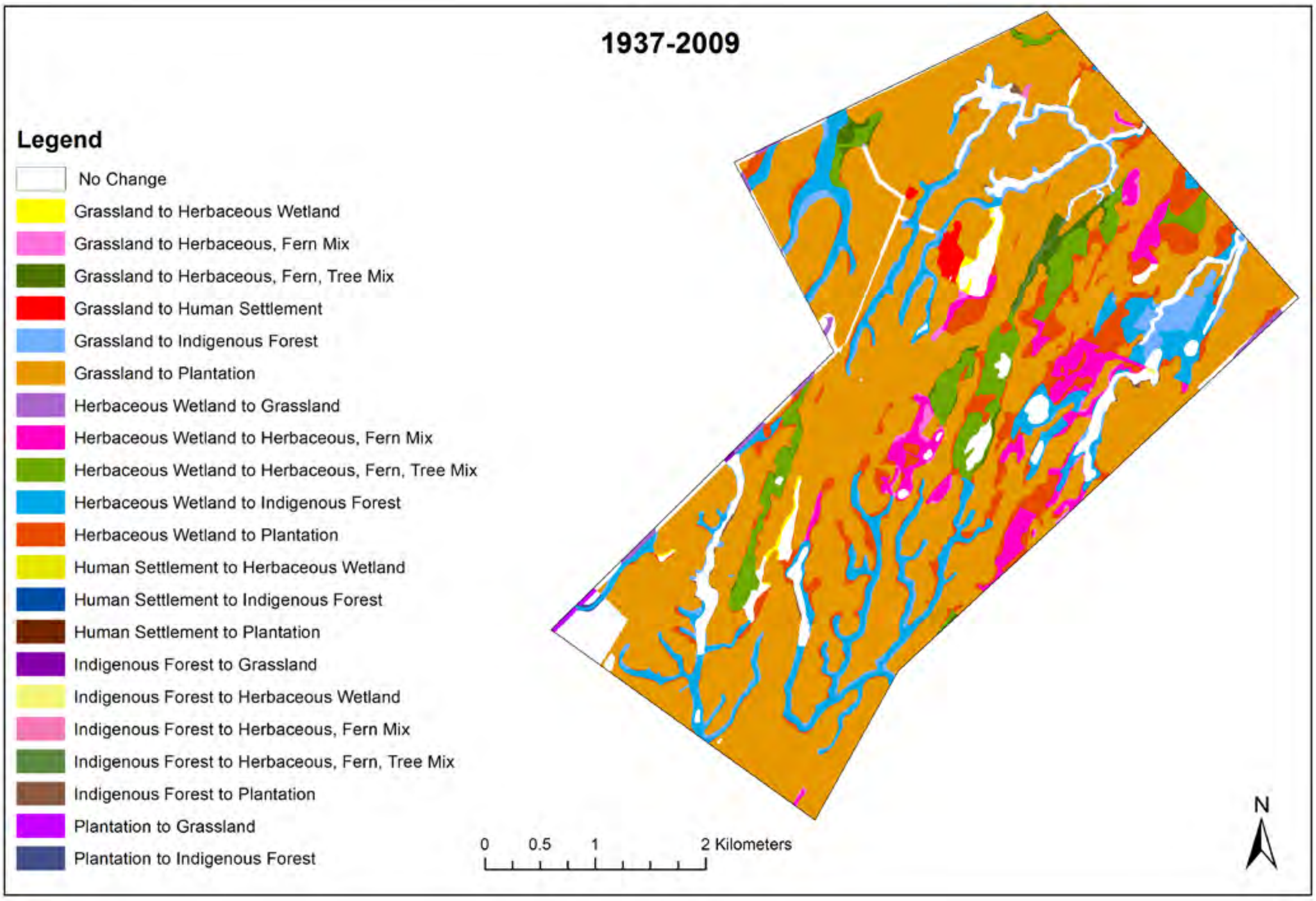


Figure 2.7: Land cover change maps highlighting changes from one land cover to another (1937, 1970 and 2009) continued.

Table 2.2: Contributors to the net change (ha) in herbaceous wetlands from 1937 to 2009. Each number pertains to the amount (ha) lost in herbaceous wetlands due to a conversion to a different land cover classes

Land-cover classes	1937-1970	1970-2009	1937-2009
Grassland	-33.05	-1	-8.76
Indigenous Forest	-62.57	-45.75	-181.43
Plantation	-361.46	-7.94	-166.96
Herbaceous, Fern Mix	0	-18.27	-75.2
Herbaceous, Fern, Tree Mix	0	-30.32	-97.98

On examining the differences in vegetation structure of wetlands with differing fire regimes and disturbance, described in this context as the conversion to plantation and clear felling, wetlands which have experienced fire seem to have maintained herbaceous vegetation compared to wetlands which have not experienced any fire (Table 2.3). All the wetlands that were converted to plantation and clear felled without fire have changed in vegetation structure from low closed herbaceous vegetation to short forest (Table 2.3). The wetlands which were not converted to plantation have maintained a largely open low vegetation structure; with most of these wetlands having mosaics of tree clusters and mainly low closed herbaceous vegetation. Z42, with a consistent biennial fire regime, is the only wetland that is without any tree species in it (Fig. 2.6). The wetlands which were converted to plantation but have since been burned have changed into a mosaic of low herbaceous vegetation, fern and low woody vegetation. With fire suppression, vegetation undergoes succession from herbaceous vegetation into a matrix with herbaceous vegetation, fern and tree species and eventually into a forest (Fig. 2.6).

Table 2.3: Wetland classification along with the summary of disturbance history. Structure is classified according to Edwards Classification System (Edwards, 1983). See appendix 3

Wetland Name	Converted to plantation and clear felled/Not	No. Of Burns in 30years	Wetland Structure
Z32	X	1	Low closed wetland//Short open woodland
Z33	X	0	Low closed wetland//Low sparse woodland
Z34	✓	2	Short closed woodland
Z37	✓	0	Short forest
Z38	✓	0	Short forest
Z41	✓	3	Short closed woodland//low closed wetland
Z42	X	7	Short closed wetland
Z44	✓	0	Short forest
Z49	X	1	Low closed wetland//short open woodland
Z50	✓	1	Low open woodland//low closed wetland
Z51	✓	0	Low closed woodland//low closed wetland

***// denotes a matrix. Dominant vegetation type appears first.**

Figure 2.8: A succession that occurs in these wetlands as they change from herbaceous vegetation to forests with the declining use of fire as a management tool. a). Z42 burned 7x b). Z41 burned 3x c). Z38 did not burn in 30 years of management history.

2.4 Discussion

2.4.1 Land cover change

According to Otukei and Blaschke (2010), land cover change is regarded as the single most important variable of global change affecting ecological systems with an impact on the environment that is as large as that associated with climate change. The result of this study depicts that 92.4% of the landscape has been altered, indicating a great degree of habitat destruction and ecosystem change. Anthropogenic factors, such as afforestation, have become significant as causes of change to the earth's surface (Chapin *et al*., 2000; Fanan *et al*., 2011). The greatest degree of change in this landscape is accounted for through the change from grassland and herbaceous wetland to timber plantation and the spread of indigenous forest indicated by an increase of 71% and 11% increase respectively. This coincides with the current thinking that states that anthropogenic factors are the greatest causes of change on the earth's surface (Tilman and Lehman, 2001; Bunn and Arthington *et al*., 2002; Troell *et al*., 2005; Miller and Spoolman, 2009; Chapin *et al*., 2010; Fanan *et al*., 2011). This is a total shift in ecosystem function as the main change is from a mainly herbaceous ecosystem which uses less water to a forested ecosystem which uses substantially more water (Richardson and van Wilgen, 2004; Dye *et al*., 2008).

Helmschrot (2005) states that large scale plantations have both hydrological effects, which include runoff reduction and water table fluctuations and ecological effects such as drying out wetlands and the destruction of natural habitats. As a result of the change in vegetation structure, this landscape is subsequently drier than it used to be when herbaceous wetlands were prevalent in the landscape. This is due to higher evapotranspiration rates (1100mm or more) of the evergreen, deep rooting forestry trees compared to grass and shrubs which have evapotranspiration rates of approximately 700mm (Dye *et al*., 2008). In the study done by Helmschrot (2005), results indicated that forest plantations reduced water availability in wetlands by amounts ranging from 10.6% to 21.5% due to higher water interception and evapotranspiration rates, with these figures doubling in small sized wetlands such as those in the Kwambonambi landscape. Wetlands get either temporary, seasonally or permanently flooded (Kirkman, 1995; Mitsch and Gosselink, 2000) and this is considered a disturbance regime which prevents tree species encroaching into the wetland (Kirkman, 1995). As shown by Kirkman (1992) where longer dry periods contributed to the encroaching of tree species into the wetlands, the result of the drying of this landscape has contributed to a shift in the hydrological disturbance regime (lack of persistent inundated periods and persistent dry periods) of this area which has contributed to the increase in forest species into the wetlands. The hydrological regime - the depth and duration of flooded conditions - is attributed to be the major environmental variable contributing to the structural and functional diversity of wetlands (Kirkman, 1995; Mitsch and Gosselink, 2000) as inundated conditions prevent tree species from encroaching into the wetlands.

2.4.2 Fire as a Wetland management tool

Bond and Keeley (2005) stated that most grassland ecosystems on earth have the climate potential to become forest but consumer controls such as fire control the tree biomass in these systems. This particularly applies to higher rainfall areas such as Kwambonambi with high summer rainfall (Bond *et al*., 2003a). With this landscape becoming drier, these wetlands presumably started to behave like moist grasslands which require fire as a management tool (Titshall *et al*., 2000; Uys *et al*., 2004). Uys *et al*. (2004) compared species richness in grasslands with different fire regimes from three different long-term plots and found no tree species in grasslands with a regular fire regime. This is also true in this landscape as the same pattern is observed. The herbaceous areas which remained herbaceous were those which have experienced fire as a management tool or burned by accident. According to Clark and Wilson (2001), fire is frequently used as a tool to prevent the invasion of woody forest species into wetlands as in grasslands, though the influence of fire on wetland vegetation is not prevalent in the literature. To confirm this, Clark and Wilson (2001) investigated fire as a wetland management tool, especially regarding the potential of fire to inhibit the invasion of woody species in the wetlands. The study concluded that fire was an efficient tool in managing the encroachment of woody species, though it favoured certain wetland species over others.

Due to the characteristics of fire such as the intensity and frequency, and the physical characteristics of the landscape, fire (along with other biotic conditions) is considered a factor that shapes the species composition, age, and canopy structure of many ecosystems (Higgins *et al.*, 2000; Tilman and Lehman, 2001; Uys *et al.*, 2004; Heinl *et al.*, 2007). This is true of the Kwambonambi wetlands where frequent burns have maintained the herbaceous structure of the wetlands compared to those which have been burned infrequently which have turned into a matrix of herbaceous species, ferns species and forest species. The Kwambonambi wetlands which have not experienced fire have mainly changed to indigenous forest. The direction of change from one wetland vegetation type to another is driven by the deviation from an average frequency or severity of fire during low flooding or drought periods (Kirkman, 1995), which the Kwambonambi wetlands are currently experiencing as a result of the plantation drying the wetlands out. Kirkman (1992) found that vegetation patterns shift spatially during decade long dry periods. During this period, upland species encroach along the wetland margins as they become dry and as the soil surface is exposed which causes a decline in aquatic species (Kirkman, 1992). This demonstrates how important fire is in wetland management especially in dry periods, particularly in most afforested landscapes such as Kwambonambi where the afforestation contributes to further drying of the landscape. It is therefore crucial to identify factors triggering apparent trends in land cover change and the extent of that change to better manage the ecosystem.

Wetland management in this landscape becomes a somewhat difficult task to do in an area which historically was occupied by both indigenous (swamp) forest and herbaceous wetland. To encourage wetland diversity of this landscape through appropriate land management, we therefore need to understand the context of species alteration of ecosystems and the consequences of a changing biodiversity as associated functional shifts occur as species with particular traits are replaced by other species with different traits. In this study remote sensing has played a crucial role in providing context to which land management could draw on to better manage this ecosystem. As both indigenous forest and herbaceous wetland occurred historically, an understanding of their historic extent can now direct the areas where fire should be applied as a management tool and areas in which fire should be suppressed. According to West *et al*. (2009), land managers require the knowledge of the baseline conditions and subsequent patterns of change to complete organizational objectives such as restoring native species and eliminating invasive species which this study has now provided for this landscape.

2.5 Conclusion

Henkel *et al.* (1936) described this area as windswept and subject to regular fire which prevents the extension of forest. They described the wetlands in Kwambonambi area as being characterised by sedges and grasses with swamp forest found in drainage lines which consists of trees, climbers and ferns. This is evident in our classified map of 1937. Currently this area is covered with mostly forest species both indigenous and timber plantation species. Indigenous forest has increased threefold in extent into areas which were historically herbaceous wetland, causing a substantial loss of this vegetation type. Grassland, the most abundant vegetation type in 1937, has now largely been converted into plantation forest and remains only in frequently burnt firebreaks.

The change of this large a scale requires the understanding and predicting the effects of land cover change on biodiversity and ecosystem function. The aim of this study was meant to investigate the landscape scale changes in vegetation structure in Kwambonambi, specifically the wetlands, with the need to evaluate the effectiveness of the current land management on this ecosystem as this ultimately effects biodiversity and ecosystem function. The large-scale changes in vegetation structure that have occurred in this landscape have highly altered ecosystem function and caused a loss of an endangered ecosystem. Long-term ecological research has revealed that the legacies of historic land-use activities continue to influence the long-term composition, structure, and function of ecosystems decades after the activity has ceased. This is a trend observed in this landscape as the removal of plantation trees in areas which were historically herbaceous wetland did not revert back to their historic vegetation but were invaded by swamp forest species which had a seed source in the landscape. The herbaceous areas in the landscape which have maintained their structure are those which were not changed to another land cover class and those which have had fire as a management strategy, signifying the ecological importance of fire in this ecosystem especially with the drying effect the land cover changes have had on this ecosystem. This study demonstrates how the suppression of fire in afforested landscapes play an important role in favouring forest species over fire-dependent herbaceous vegetation.

The conclusion therefore is that land cover change, the change to timber plantation which is linked with fire suppression and the drying of the landscape is the main cause of the change in wetland vegetation structure. Helmschrot (2005) describes the hydrological and ecological effects of plantations have on wetland systems; it is recommended that the hydrological effects be investigated further in this system to better inform management decisions. Land managers can then make appropriate decisions regarding the management of these wetlands with a better understanding of the different responses of wetland vegetation to varying fire regimes and the effect plantation has on the overall landscape. The decision could be to change to a plantation species that consumes less water or include fire into the wetland management strategy or both. This study demonstrates how important multi-temporal research is in directing management decisions, signifying the importance of understanding present ecological conditions in a context that feature past land use and natural disturbance.

Chapter 3

The effect of fire on wetland vegetation species composition and structure

3.1 Introduction

3.1.1 Background

Ecosystems can undergo regime shifts where they change from one state into another (Folke *et al*., 2004). Regime shifts are defined as large, persistent changes in the structure and function of ecosystems, with substantive impacts on the suite of ecosystem services provided by these systems (Biggs *et al*., 2011). This can have important implications for the formulation of management strategies, if systems develop into undesirable states from a human perspective, especially if they have a high resistance to restoration efforts (Troell *et al*., 2005). From the previous chapter it is evident that there is an ecosystem regime shift in the Kwambonambi wetlands located on the Zululand coastal plains of South Africa.

The mechanisms that promote regime shifts from herbaceous wetland to forest are unclear, thus a thorough understanding of the factors that influence structure of wetland communities is urgently required to guide management efforts. This is especially important as wetlands are sensitive to degradation and transformation brought on by changes in vegetation structure and composition, which can influence their function and ultimately how they contribute to human welfare and well-being (Turner *et al*., 2003). The Zululand coastal plains of South Africa comprise coastal forest, grassland and extensive wetlands, historically dominated by herbaceous vegetation (Henkel *et al*., 1936). Findings from the previous chapter have shown that, in recent decades, vegetation in these wetlands has changed in composition and structure, becoming increasingly woody. Fire suppression, the change to plantation followed by plantation removal (disturbance) in the wetlands and a drying out of the ecosystem were singled out as possible explanations for the change in vegetation structure in the previous chapter. This chapter will focus on the effects of fire on vegetation to better understand the drivers of the observed regime shifts in these wetlands.

Fire is a natural phenomenon in shaping the landscape, hence an important determinant of plant diversity and vegetation structure in regions where it occurs (Hoffman and O’Connor, 1999; Heinl *et al*., 2007). Fire as a disturbance has played an essential role in the expansion of the grassy biomes during the Miocene epoch (Keeley and Rundel, 2005), so it is not surprising that so many of these biomes are highly fire tolerant and often require fire for survival. These disturbance-maintained grassy systems therefore have possible alternative states and many of these ecosystems are currently experiencing a shift in "ecological states/regimes" from grassy ecosystems into shrublands and forests (Clark and Wilson, 2001; Groffman *et al.*, 2006; Middleton *et al.*, 2006; Weigand *et al.*, 2006; Martin and Kirkman, 2009).

As a consequence, there is great interest in identifying ecological thresholds, defined as the point at which there is an abrupt change in a quality (such as the maintenance of a particular species), property or where small changes in a driver (for example, fire, landscape fragmentation) may produce large responses in the ecosystem (Folke *et al.*, 2004; Groffman *et al.*, 2006; Martin and Kirkman, 2009). The concept of ecological thresholds emerged from the idea that ecosystems often exhibit multiple ''stable'' states, depending on environmental conditions illustrated in Fig. 3.1 (Folke *et al.*, 2004; Groffman *et al.*, 2006).

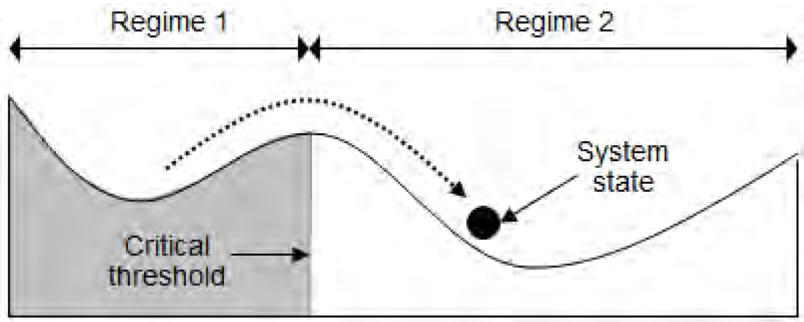


Figure 3.1: Illustration of regime shifts from one state into another (Biggs et al., 2011). States are represented by the ball and the valleys represent different regime or a systems structure and ultimately function.

Many studies have investigated the effects of fire as a driver of vegetation structure and many of these return conflicting results due to the variety of vegetation types (Heinl *et al.*, 2007). In grassland and savanna ecosystems across Africa the driving factor that determines woody cover percentage (vegetation structure) is the mean annual precipitation (MAP) of an area (Sankaran *et al.*, 2005), based on collated data from 854 sites across Africa. Water availability in areas where the MAP is less than 650 mm per year was found to limit woody cover percentage, whereas in areas with a MAP of 650 mm per year and higher (which includes the Zululand coastal plains), woody cover percentage is determined by mainly fire (Sankaran *et al.*, 2005). This means that in areas where water availability is not a limiting factor, fire is the main factor limiting woody cover percentage. In a closer investigation of vegetation and fire in grass dominated ecosystems through a collation of results from long-term fire experiments, Bond *et al.* (2003a) showed that following the long-term suppression of fire, grassy vegetation in areas with a MAP of greater than 650 mm per year tended to shift to fire-sensitive forest vegetation, whereas in areas with a MAP of less than 650 mm per year the observed changes were in tree size and density but did not shift to forest.

What does this then mean for wetlands which are, or were, historically nested within grassland and savanna ecosystems, and therefore have developed under frequent fire? Wetlands are predominantly herbaceous dominated, fire-prone and fire dependent ecosystems. From the previous chapter we know the Kwambonambi wetlands were historically herbaceous and according to Henkel *et al.* (1936), comprised mainly of grass and sedges. According to Bond and Keeley (2005) fire has a considerable effect on the structure and dynamics of plant communities and is a critical selection pressure on plant traits. This suggests that understanding the response of vegetation to fire should be a prerequisite when developing management strategies for all fire dependent ecosystems for conservation, including wetlands.

Wetlands, unlike grasslands or savannas, have higher soil water availability, where the wet season is extended by elevated soil moisture levels, and therefore water availability is unlikely to be the limiting factor for woody cover percentage. In wetlands the level of inundation/soil saturation or the period of inundation/soil saturation naturally limits trees that are not adapted to waterlogged soils from encroaching into the wetlands as most trees cannot grow in soil saturated with water. In Kwambonambi the trees encroaching the wetlands are swamp forest species (such as *Macaranga capensis* and *Bridelia micrantha*) which are adapted to waterlogged soils. In areas where water availability becomes less of a factor, the studies cited above by Sankaran *et al.* (2005) and Bond *et al.* (2003a) who investigated the determinants of woody cover in African savannas and the controlling driver of South African vegetation, respectively, suggest that fire would be the determining factor influencing woody cover. Is this the case in wetlands?

Martin and Kirkman (2009), studying small depression wetlands, concluded that fire is a determining factor in influencing woody cover in wetlands. The wetlands in this study, comparable to the Kwambonambi wetlands, were historically herbaceous, fire maintained wetlands, but have seen a shift in system state as they have been invaded by hardwood forest species. During periods of extended fire suppression in these wetlands, the herbaceous vegetation, which is highly flammable, was outcompeted, and entirely replaced by hardwood forest species, which have a low flammability and impede the spread of fire. Changes in the regime of these wetlands, the herbaceous vegetation-fire feedback mechanism, caused the vegetation to move across an ecological threshold and into an alternative state where the vegetation itself excludes fire. The removal of the hardwood forest species restored the herbaceous vegetation feedback mechanism and ultimately restored the system back to its historic state. Similar results were found in an investigation by Clark and Wilson (2001) of wetland prairie plant species in responses to experimental burning, hand-removal of woody species, and mowing with removal of cut material. In their study, prescribed burning produced the greatest reduction in cover of woody species, effective in limiting the abundance of non-native herbaceous plants, and promoted the cover of native wetland species (Clark and Wilson, 2001). In their study some of the invading woody species, similar as those in Kwambonambi, are also adapted to flooded conditions.

Prescribed burning is an important management tool in herbaceous systems where it maintains grass sward vigour, suppresses and removes undesirable woody elements and reduces the risk of wildfires by reducing fuel accumulation (Adie *et al.*, 2011). An investigation of the effect of fire on trees in grasslands revealed higher tree mortality in trees shorter than 2m and increasing fire intensities produced higher percentages of topkill (Trollope, 2007) indicating the effect of fire on vegetation depends on the physical properties of the fire and fire behaviour. This implies that studies of vegetation and fire should also investigate fire behaviour and fire intensity to determine the most effective burn for the management of encroaching woody species in herbaceous systems.

3.1.2 Research Gaps

In the previous chapter significant increases of fern prevalence were observed in these wetlands and this could be a cause for concern. Adie *et al.* (2011) showed that the presence of *Pteridium aquilinum* (bracken fern) aided in the transition of grassland to forest in periods of long fire suppression and through the failure of bracken fern to ignite on cool, moist days, providing establishment opportunities for resprouting early-successional forest species. Thus the question for Kwambonambi relates to whether ferns might aid the transition from herbaceous wetland into forest. This is a cause for concern as plantation forests are areas of fire suppression where any prescribed burning usually occurs on cool days. Bracken fern is described as a landscape transformer which plays a pivotal role in montane grasslands by directing plant community development down alternative, and irreversible, successional pathways from grassland to forest (Adie *et al.*, 2011). The particular fern in the Kwambonambi wetlands is *Stenochlaena tenuifolia*, which, along with other ferns which are not as prevalent, is thought to aid the successional transition from the herbaceous state to a woody state by limiting fire spread as they remain vigorous long after the grass has lost its vigour in winter. Ferns are natural components of the swamp forest, forming a dense understory in the forest but their role in wetland structuring is not known, and thus it is important to determine their role in order to make informed management decisions.

Fire frequency, along with hydrology, organic matter accumulation and origin of the water source are the four environmental variables presumed to contribute to the overall structural and functional diversity of wetlands (Mitsch and Gosselink, 2000). The hydrological regime, i.e. the depth and duration of flooded conditions and the duration of saturation of the shallow soil layers, is attributed to be the major environmental variable that contributes to the structure of wetlands (Kirkman, 1995; Mitsch and Gosselink, 2000). In the floodplains of the Okavango Delta, an increased fire frequency was found to be an importance driver in vegetation structure in the drying floodplains compared to active flood plains where flooding was the main driver (Heinl *et al.*, 2007). Drying floodplains were defined as floodplains which had not been inundated for more than 10 years, while active floodplains are flooded at least every second year (Heinl *et al.*, 2007). Despite the importance of fire as an ecological driver of South African wetlands, very little research has been undertaken on the effect of fire on vegetation composition and structure in wetlands. The same amount of research needs to go into investigating fire and vegetation in wetlands, as in grasslands, where many long-term fire trials have contributed to the management of these systems. The greatest urgency for such research is for the wetland ecosystems most strongly dependent on fire for maintaining their composition and structure.

According to the National Biodiversity Assessment (2011) wetland ecosystems are the most threatened of all ecosystem types, making their conservation and management important especially for the water security of the country (Nel and Driver, 2012). There is probably a need to investigate local effects of fire on differing wetlands as they all function slightly differently to one another. A management practice important to smaller depression wetlands may not necessarily be important to large floodplains or peat accumulating wetlands. It is therefore important to provide managers of wetlands with the appropriate information for informed decision making regarding the management of wetlands.

3.1.3. Aims and Objectives

3.1.3.1 Aim:

The aim of this study is to characterise wetland vegetation species composition and structure of a sample of Kwambonambi wetlands with differing disturbance histories and experimentally determine the short-term effects of a single fire event.

3.1.3.2 Objectives:

To meet the aim of the study, the following objectives have been set:

- To characterise the vegetation composition and structure of two wetlands in relation to fire and other environmental variables.
- To determine the effect of fire on tree density and size class distribution
- To investigate the influence of ferns, particularly *Stenochlaena tenuifolia*, on fire behaviour during a fire event

3.1.3.3 Hypotheses:

H_o: Fire has no effect on species composition and structure

H_o: A fire event does not alter tree density or the size class distribution of the trees

H_o: Ferns do not influence fire behaviour

3.2 Methods and Materials

3.2.1 Study design

Sites were selected after an initial survey of the wetlands in the plantation. For the purpose of the study, wetlands with similar hydro-geomorphic settings to Langepan (which is Z42, the biodiversity conservation priority for the area) were selected. This was done to minimize any variability regarding “non-fire related” variables being of any influence in the vegetation composition and structure of the wetlands selected for the study. This initial survey was used to help determine the plot size for sampling, how the different growth forms will be measured, whether the sampling will differ for the more herbaceous wetlands to the wetlands highly invaded by fern and wooded species and finally to document the different disturbance histories required for the study from the plantation managers.

The preliminary survey of the forest wetlands revealed numerous issues which then affected the final sampling procedure. These issues were:

1. There has been mechanical removal of alien invasive species and indigenous tree species in the wetlands as part of forest management.
2. Locating the fire records of the wetlands was a difficult task, as they are either lost or do not exist.
3. As a new management strategy the plantation managers have started treating the wetlands highly invaded by ferns with a herbicide and chopping down trees for an efficient burn. This is to ensure that the vegetation is dry as winter sets in late in the coastal regions and the ferns tend to not dry out.
4. Burning the experimental wetlands during the study period proved to be a difficult task for the foresters due to oscillating weather conditions switching from too hot and windy to burn in a plantation forest to extended wet/damp conditions which prevented the burn.

3.2.2 Field datasets:

Five wetlands were initially chosen for the purpose of the study, each with varying levels of fire disturbance, removal history and alien invasive clearance history. As a consequence of the four issues mentioned above, only two of the five wetlands (Z34 and Z49) could be selected to perform the burn experiment. Z34 was once converted into a *Pinus elliottii* plantation forest in the early 1970s. Plantation forest trees were clear-felled out of the wetland approximately 25 years ago after a single rotation. Z49, according to descriptions from the foresters, was permanently inundated for the entire year until approximately 15 years ago. Z34 consists of substantially more trees that Z49 (Table 3.1). These wetlands comprise of ferns and trees on the edges of the wetland enclosing hygrophilic grassland.

Table 3.1: Wetland site descriptions

Z34	Z49

Mature trees occupied the edges of the wetland and tree seedlings encroaching further into the wetland.	Trees occupied mainly the wetland edges
Wetland is completely enclosed by plantation	Wetland is partially enclosed by plantation and intersected by one of the main forest roads.
Gentle gradient	Gradient slightly sloping into the wetland especially on the side of the road
Width is approximately 80 m	Width is approximately 120m

Within each of these two wetlands, two different treatments of 50m x 50m each were demarcated and set up. The two different treatments were "treated with herbicide and burned" and a treatment just burned. The ferns are believed to change fire behaviour by limiting the spread of fire as they retain vigour longer than the grass and thus threating the treatment with a herbicide is meant to kill the ferns. These treatment sites were separated by a minimum 10m fire break. As there were two different vegetation strata (trees and herbaceous species) to be sampled. The sampling was done across the wetland to encompass the varying levels of wetness within each wetland. Four transects ran across the treatments 10m apart and were of variable lengths to include a set buffer on either side of the wetland to remove edge effects. The minimum length of each transect was 50m.

For sampling woody species, a 50 x 4m belt transect was surveyed across the wetland to measure tree characteristics (Fig. 3.2). These measurements included measuring the canopy cover and the height of each individual tree. This was done using a measuring rod. Canopy cover was measured across 2 perpendicular axes to get the average canopy diameter.

Herbaceous species were randomly sampled within twenty five 0.5 x 0.5m quadrats within the same 50 x 4m belt transects (Fig. 3.2). Within each quadrat, the height of the vegetation was noted, each species were recorded and percentage aerial cover for each species was estimated using a modification of the decimal scale of Londo (1984).

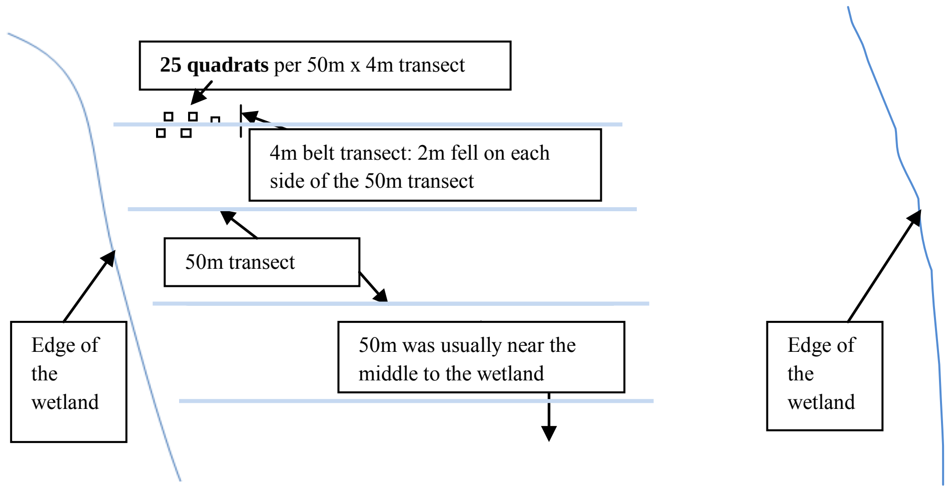


Figure 3.2: Diagram to illustrate the sampling set up for the research.

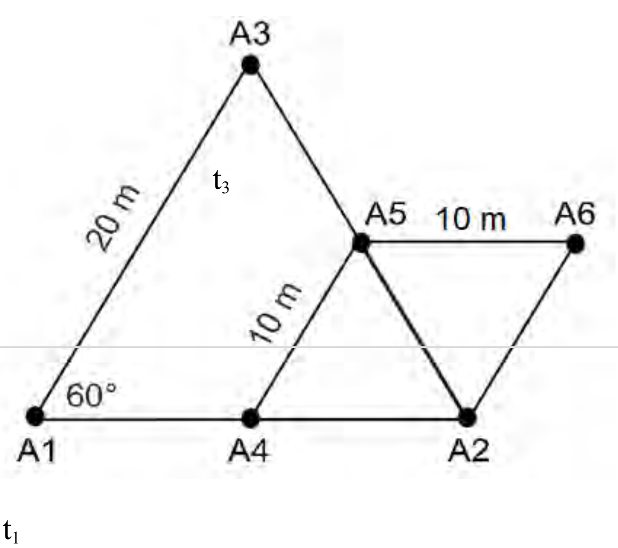
Vegetation composition and structure were described together with physical descriptors of the wetland. Direct gradient analyses were performed on the data through which relationships between the vegetation and the environmental variables were investigated. Constrained canonical correspondence analyses (CCA) were carried out with species and environmental data to investigate the relationships between species, samples and the influence the environmental variables have on species occurrence and distributions. The aim of constrained ordination is to find the variability in species composition that can be explained by the measured environmental variables. A Monte Carlo permutation test, using 999 unrestricted permutations, was used to test whether the included environmental variables had a significant effect on the species composition. These analyses were performed using CANOCO (Version 4.56, Wageningen, The Netherlands). To compare the effect of fire on the vegetation structure of the two wetland sites t-tests were performed on the tree data to determine the statistical difference between tree density and the average height of trees before and after the fire event. This was performed using IBM SPSS Statistics (Version 21.0, New York, United States). Shannon-Weiner diversity index was calculated for both wetlands, before and after the fire event.

Pre-fire measurements

To measure the short-term effect of fire on species composition and structure, burn experiments were carried out. Due to unforeseen circumstances the experiment could not be fully executed. This was due to the weather conditions oscillating between unusually wet for the season, being too hot to burn for plantation forest safety standards and mechanical failure of essential fire fighting equipment. Only the untreated (no herbicide applied) sites in both wetlands could be burned.

To describe and compare the effect of fire on the vegetation of both wetlands the fire intensity of each fire was measured. Fire intensity is the release of energy from organic matter during combustion (Keeley, 2009; Adie *et al*., 2011). To describe fire intensity, fireline intensity and temperature were used. Fireline intensity I=H * w * r) is the radiant energy in the fire front (Adie *et al*., 2011), (I; kW m^{-1}) and is the product of the fuel heat yield (H; J g^{-1}), the fuel biomass (w; kg m^{-2}) and the rate of spread (ROS) (r; ms^{-1}). The calorific value of the grass and fern are similar, and so for the purpose of this study 18 500 J g^{-1} was the value used for the calorific value (H) adapted from Adie *et al.* (2011). To estimate fuel biomass all above-ground vegetation was clipped within five 0.5 x 0.5m quadrats the day before the experiment per wetland site. Vegetation clipping involves cutting the herbaceous species within a quadrat to a height of 10 mm above ground level. Grass and fern moisture content was determined by collection samples of ~ 20g at each treatment before the burn. Five replications were done for grass and ferns. These were in double sealed plastic bags and measured in field using a mobile balance. These samples (both the biomass and moisture content samples) were oven dried (48 h at 70°C) before weighing to calculate fuel biomass and percent moisture. The percentage moisture content was determined as the difference between the field mass and the mass after drying. This was done to aid in the explanation of the possible differences in fire intensity and subsequently the differences in the effect of fire.

To record soil-surface temperature DS19 22T temperature logger iButtons (Maxim Integrated Products, www.maxim-ic.com) were used. The iButtons are temperature-residence-time meters that measure temperature from 0 to 125°C (± 2°C) while keeping track of the time. Above this temperature, the iButtons get incinerated. To calculate the rate of spread the times the fire reached three different points in the landscape being burned were required.



D

t_2

Figure 3.3: Diagram to illustrate the three equilateral triangle set up to measure the rate of spread a fire.

To achieve this, three equilateral triangles were set up; one was 20m and the other two were 10m each (Fig. 3.3), as in Adie *et al.* (2011) to calculate the rate of spread of the fire.
The rate of spread is calculated using the following formulae:

$$\theta = \tan^{-1}\left[\left(\frac{t_3 - t_1}{t_2 - t_1}\right)\left(\frac{b}{c\sin A}\right) - \left(\frac{1}{\tan A}\right)\right];\ t_2 \neq t_1 \qquad (1)$$

$$r = \frac{D\cos\theta}{t_2 - t_1};\ t_2 \neq t_1 \qquad (2)$$

Where,
t_1, t_2, t_3 = times that a fire arrives at the first, second and third vertices of the equilateral triangle,
D = distance between the points,
θ = the angle of spread relative to a base line between t_1 and t_2,
r = rate of spread

The iButtons were placed at the apices of these triangles. The iButtons were set to record at a 1 s interval. The iButtons were also placed in fern patches of different sizes (patch diameter) which were measured using a measuring rod and classed by size (small, medium and large). In Z34 two sets of these triangles were set up to accommodate the two dominant grass species which were structurally distinct. Once the fire had moved across the triangle the data from the iButtons were collected. This data was then used to calculate the rate of spread and together with the measured fuel biomass, used to calculate the fire-line intensity.

Post-fire measurements

To measure combustion efficiency, three randomly selected transects of 20m were laid out in each wetland and percentage length burned in each transect was used as combustion efficiency. These three transects were laid out in an orientation that would encompass most of the site. Percentage length burned was calculated according to Williams *et al.* (1998) which is:

((the total length of transect burned) / the total transect length) * 100%.

Post fire sampling was done 5 months later. The same sampling procedure was carried out.

3.3 Results

3.3.1 Herbaceous layer characterisation

Before the fire, there were distinct differences in species composition between the two wetland sites, though there were shared species between the sites. The Monte Carlo permutation test was significant for Axis 1 and all canonical axes ($p = 0.001$), meaning that the environmental variables had a significant effect on the species composition. The variance inflation factors for all the environmental variables were low (< 2), indicating low collinearity of the environmental variables.

The different wetland sites separated out distinctly, mainly along axis 1, from Z34 samples on the right to Z49 plots on the left within the ordination space (Fig. 3.4). Axis 1, which accounted for 58.8% and 9.7% of the species-environment and species data variation respectively, was strongly related to the disturbance (fire history and conversion to plantation) variables (with species-environment correlation of 0.922) and their correlation to the other axes was considerably lower. Axis 2, accounted for 41.2% and 6.8% of the species-environment and species data variation respectively, was mainly related to the distance of the plots down the wetland with a correlation coefficient of 0.730. Species differed significantly from the edge of the wetlands to the middle of the wetlands. Axis 3 accounts for 14.3% of the species data variance. Height, added as a supplementary environmental variable, had a great influence on axis 2, contributing to 38.1% of species-environmental variance. This influence of height on the species-environment suggests there are other missing variables which were not measured. Species at edges of the wetlands tended to be taller than those in the middle of the wetlands; consisting mostly of ferns, forbs and alien invasive species. The disturbance variables had a greater effect on the species composition in Z34 where alien invasive species were more prevalent compared to Z49. The disturbances in Z34 led to increased species richness through the inclusion of alien invasive species such as *Lantana camara, Pteridium aquilinum*, *Solanum mauritianum* and forbs such as *Senecio polyanthemoides, Helichrysum longifolium and Gomphocarpus flexuosa*. Z49 was characterized with more wetland species such as wetland grasses and *Cyperaceae* than Z34 which comprises mainly of grasses and forest pioneer species such as *Trema orientalis* and *Halleria lucida*.

After the fire event, the two wetland sites still displayed distinctive differences in species composition with very little overlap in species. The environmental variables had a significant effect on species distribution, the Monte Carlo test was significant for the Axis 1 and all canonical axes ($p = 0.001$). Axis 1, accounted for 70.2% and 13.8% of the species-environment and species data variation respectively, was related mainly to the historical management (fire and plantation). The first axis was very well correlated with these disturbance variables ($r = 0.938$). Axis 2, accounted for 29.8% and 5.9% of the species-environment and species data variation respectively was mainly due to the distance into the wetland with the correlation coefficient of $r = 0.643$. Fire, indicated by the length of the arrow representing fire, had more of an effect on the species composition of the Z34 site (Fig. 3.5). The fire event in Z49 prompted the germination of *Solanum mauritianum* but also some indigenous herbaceous wetland species such as *Cyperus* and *Pycreus polystachyos* along with other grass species. Species still differed significantly from the edge of the wetlands to the middle of the wetlands. Axis 3 accounted for 15.2% of the species data variance, which was greater than the first two axes. The supplementary environmental variable after the fire occurrence, contributed 4% and 14.2 % of the species-environment variation in the axis 1 and axis 2 respectively. Height contributed to 32.6% of the species-environment relation in axis 3. After the fire event, other than *Solanum mauritianum* seedlings sprouting, most of the alien invasive species in both of the wetlands decreased; with the exception of the fern *Pteridium aquilinum.*

Species diversity before and after the fire using the Shannon Diversity index (Hmax) was 3.13 and 2.77 respectively in Z49. The Shannon Diversity index (Hmax) was 3.66 and 3.18 respectively in Z34 which is a similar trend to Z49 where species diversity was slightly lower after the fire event.

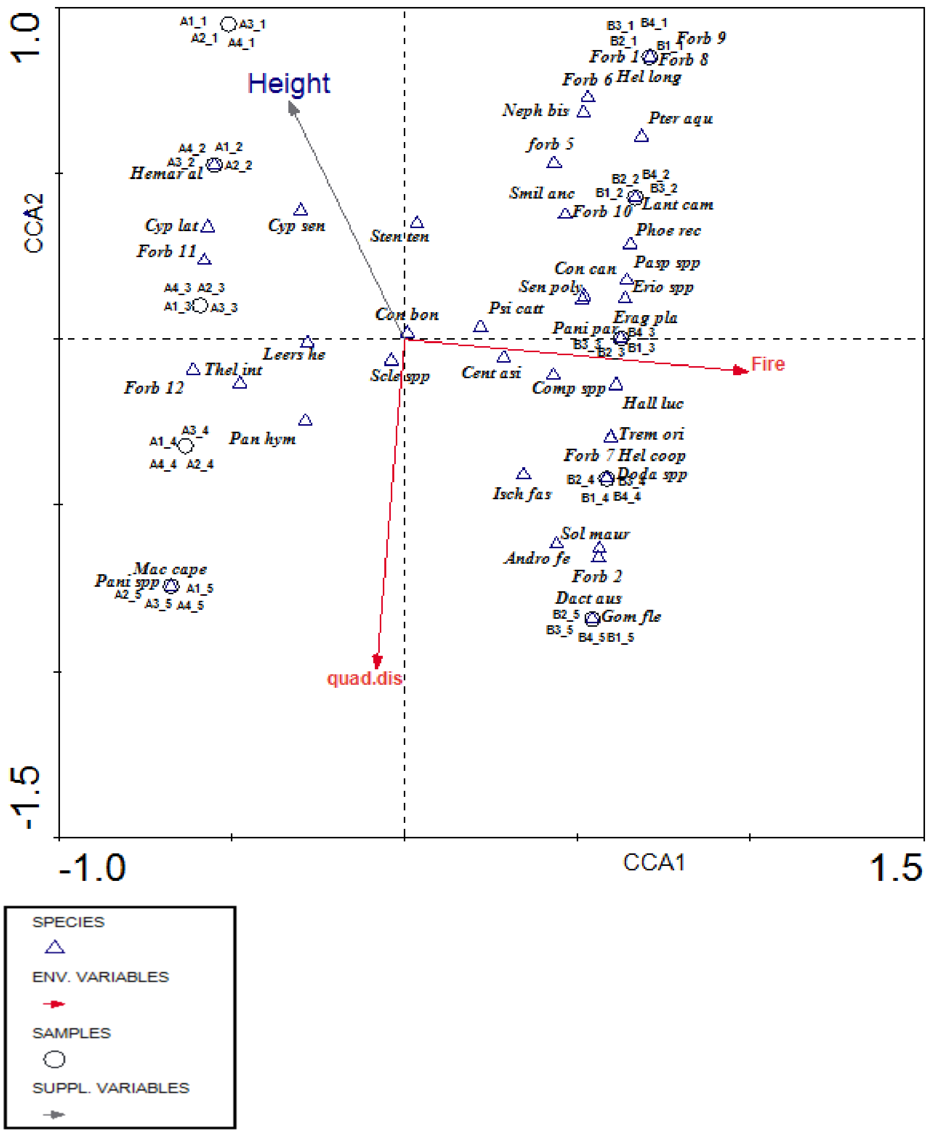


Figure 3.4: Axis 1 and 2 of a canonical correspondence analysis depicting herbaceous species assemblages in relation to the environmental variables contributing to the observed differences in species assemblages of the two wetlands before a fire event. The eigen values for axis 1 and axis 2 are 0.320 and 0.224, accounting for 58.8% and 41.2% of the environmental-species relation variability and for 9.7% and 6.8% of species variability respectively. The p value for the Monte Carlo permutation test was significant (p=0.001). The supplementary variable height contributed to 11.8% and 38.1% of the species-environment variance in axis 1 ad axis 2 respectively. Sample key: A- Z49 and B- Z34. Each transect is denoted by the first number after the wetland alphabet, for example, A1 is transect 1 of Z49. The number at the end of each sample indicates the zone at which the sample was collected (1:0-10m into the wetland, 2: 10-20m into the wetland, 3: 20-30m into the wetland, 4: 30-40m into the wetland, 5: 40-50m into the wetland). Variable key: Height-supplementary variable, quad.dis-distance of the quadrant into the wetland and Fire history (The number of times the wetland has been burned in the last 25 years). Dist-disturbed by being converted to plantation forest before (classes: Disturbed=1 and Undisturbed= 0) was removed from the diagram because it was highly correlated to the fire history. See appendix 1 for the full species names of the given acronyms shown in the figure.

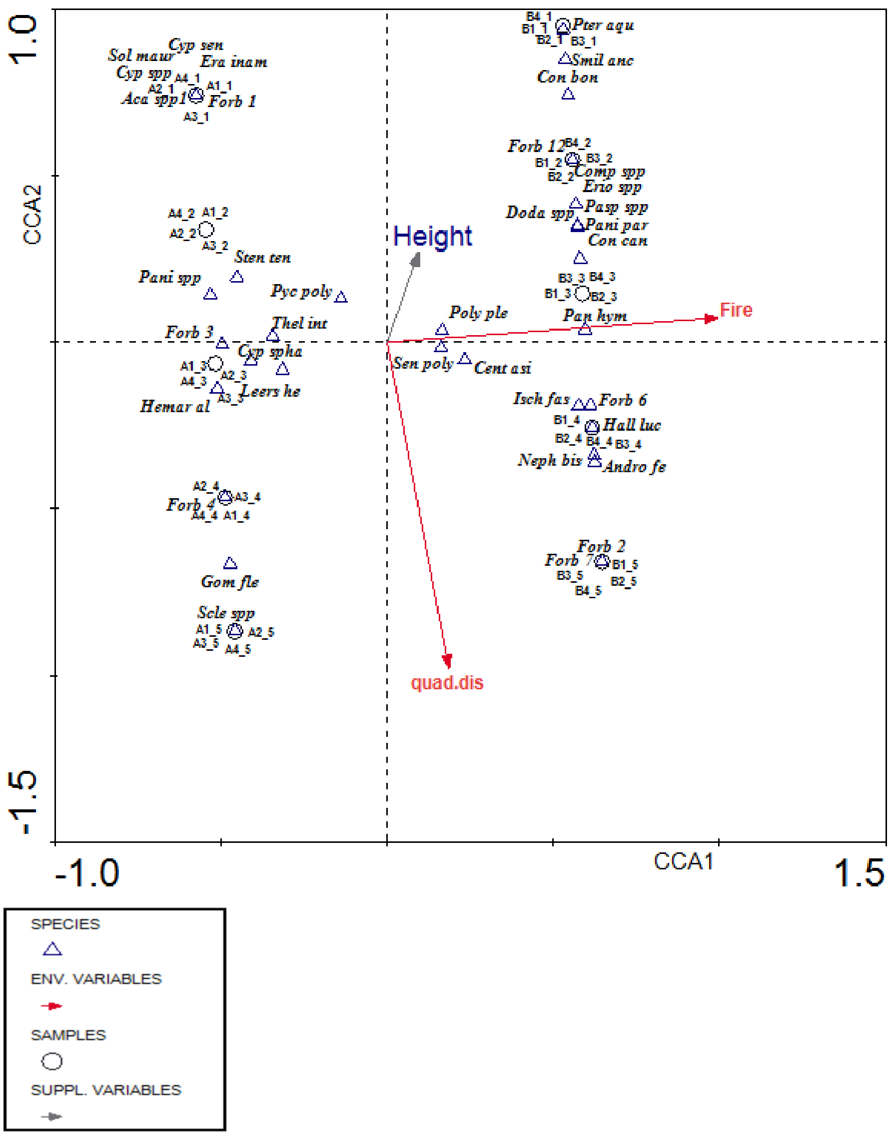


Figure 3.5: Axis 1 and 2 of a canonical correspondence analysis depicting herbaceous species assemblages in relation to the environmental variables contributing to the observed differences in species assemblages of the two wetlands after a fire event. The eigen values for axis 1 and axis 2 are 0.617 and 0.262, accounting for 70.2% and 29.8% of the environmental-species relation variability and for 13.8% and 5.9% of species variability respectively. The p value for the Monte Carlo permutation test was significant (p=0.001). The supplementary variable height contributed to 4% and 14.2% of the species-environment variance in axis 1 and axis 2 respectively. Sample key: A- Z49 and B- Z34. Each transect is denoted by the first number after the wetland alphabet, for example, A1 is transect 1 of Z49. The number at the end of each sample indicates the zone at which the sample was collected (1:0-10m into the wetland, 2: 10-20m into the wetland, 3: 20-30m into the wetland, 4: 30-40m into the wetland, 5: 40-50m into the wetland). Variable key: Height-supplementary variable, quad.dis-distance of the quadrant into the wetland and Fire history (The number of times the wetland has been burned in the last 25 years) and Dist- disturbed by being converted to plantation forest before (classes: Disturbed=1 and Undisturbed= 0) was removed from the diagram because it was highly correlated to the fire history. See appendix 1 for the full species names of the given acronyms shown in the figure.

3.3.2 Vegetation Structure

Tree density in Z34 before the burn was significantly higher (p = 0.015) than after the fire. There are certain species the fire affected more than others, specifically *Macaranga capensis, Solanum mauritianum* and *Phoenix reclinata* (Fig. 3.6a), having the greatest reduction in density. Fire was specifically detrimental to the tree saplings and seedlings of these species. The loss of these saplings (trees taller than 1m but less than 2m) and seedlings (trees 1m or less) raised the average height of the trees, evident with higher height averages after the fire with the loss of these seedlings (Fig. 3.7). This indicates that fire was ineffective in tree mortality of higher size classes, for example, the density of *Macaranga capensis* and *Bridelia micrantha* in the tallest height class remained the same before and after the fire (Fig. 3.6b). Out of the 17 tree saplings found in Z34 before the fire, only 8 of them (47%) survived the fire. The seedlings were less affected by the fire with 80% of them germinating after the fire. The majority of these seedlings that recoppiced in this wetland were *Halleria lucida* and *Trema orientalis* (Fig. 3.10).

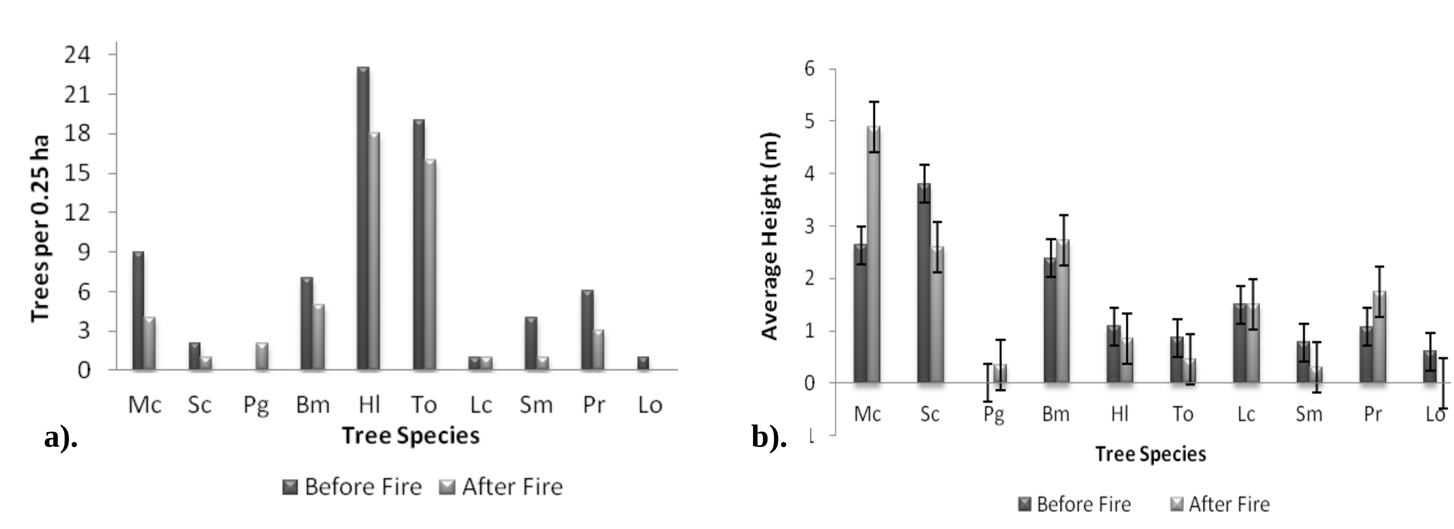


Figure 3.6: Tree density and the average height (with standard error bars) of trees in Z34 before and after a fire event 5 months later.

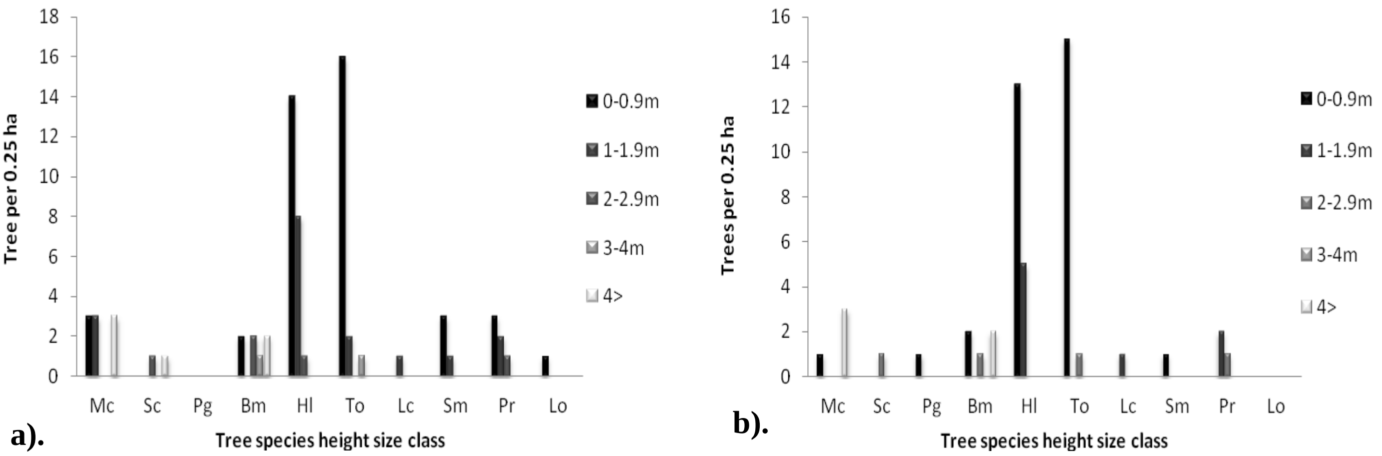


Figure 3.7: Tree density according to height size class. a): before and b): after a fire event in the Z34 site.

Tree density in Z49, before and after the fire, was not statistically different ($P > 0.05$). However, fire had a substantial effect on certain tree species densities, particularly *Syzygium cordatum, Macaranga capensis* and *Psidium guajava* (Fig. 3.8a). Fire had a positive influence on the density of *Solanum mauritianum* from 2 saplings before the fire to 12 seedlings after (Fig. 3.9). Fire had a significant effect on the average height of trees in Z49 ($p = 0.013$), but did not have this effect in Z34. To be confident of whether any apparent differences in distribution are attributable to fire Chi-squared tests were done on tree height data. These Chi-squared tests confirmed the observed changes were not by chance, fire did have a significant effect on tree height in Z49 and not in Z34. Before the fire there were 11 saplings overall, only 2 (18%) survived the fire. After the fire *Trema orientalis* seedlings germinated, and there was an increase in *Solanum mauritianum* seedlings compared to before the fire (Fig. 3.10). Trees with the higher height classes (>2 m) were significantly affected by the fire in this wetland (Fig. 3.9), only 19 seedlings and 2 saplings after the fire.

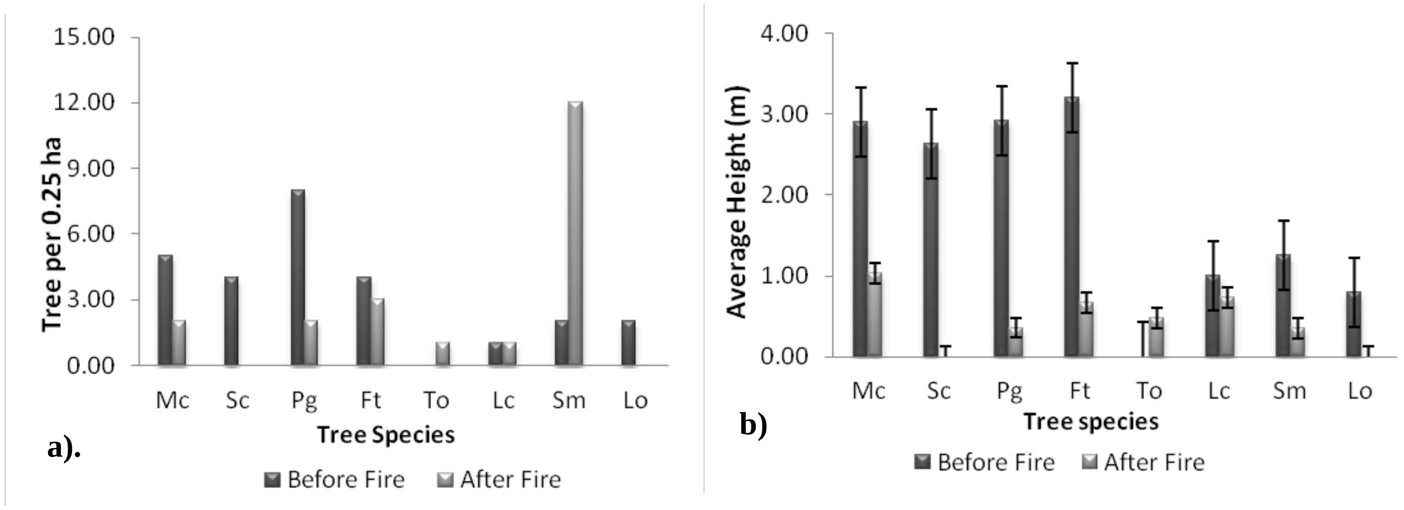


Figure 9.8: Tree density and their average height (with standard error bars) of trees in Z49 before and after a fire event 5 months later.

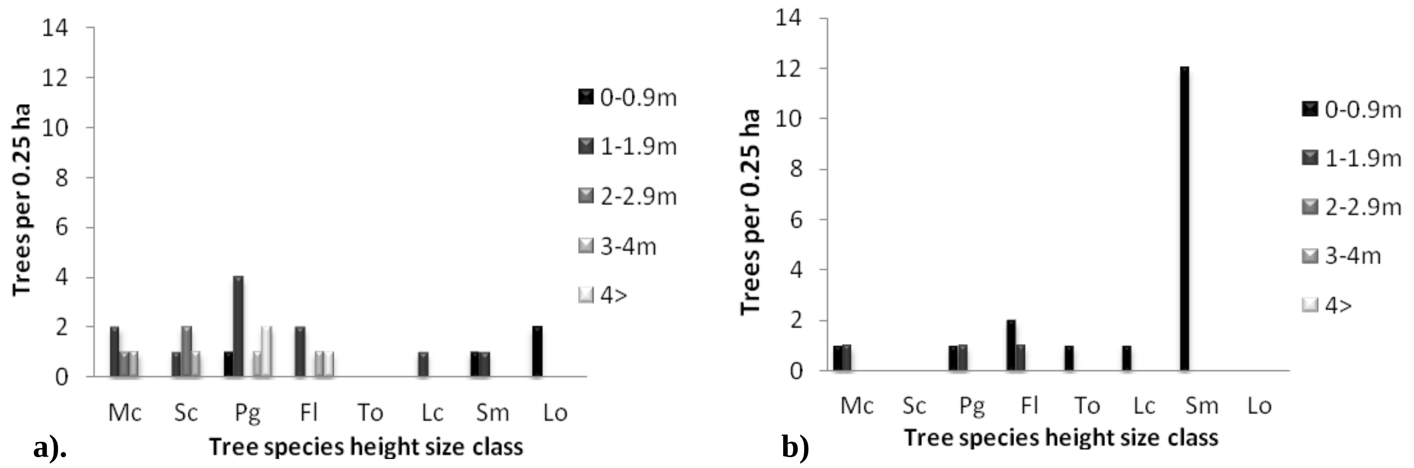


Figure 3.9: Tree density according to height size. a): before and b): after a fire event in Z49.

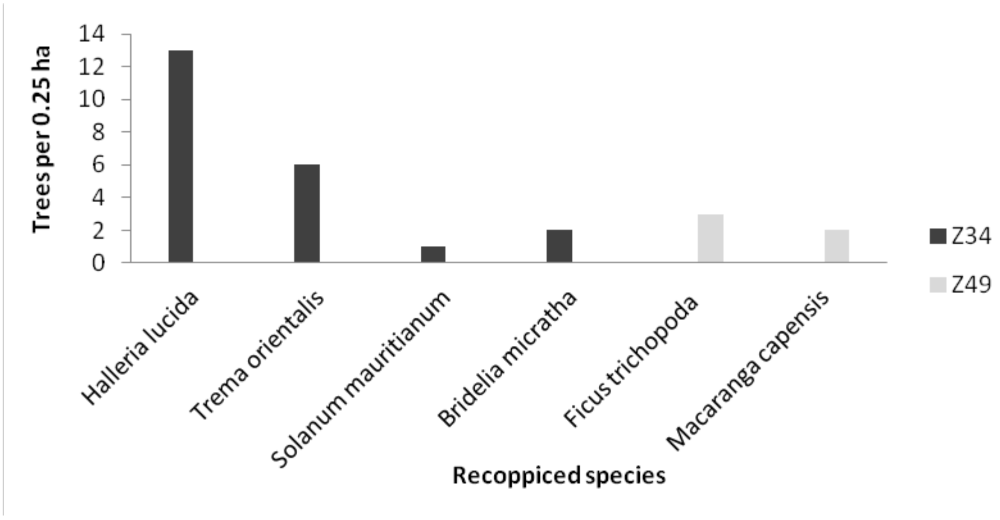


Figure 3.10: The number of trees per species to recoppice after the fire in each wetland site.

Fire intensity for both burns was measured but due to the patchiness of the burn in Z49, not all the measurements needed to calculate the rate of spread of the fire were possible. The burn in Z49 was patchy with a combustion efficiency of 62.7% compared to 95% in Z34. Despite the inability to measure rate of spread in Z49, we can deduce that the low combustion efficiency, resulting in a slow rate of spread, would have resulted in low fire intensity for this wetland.

The ferns had an influence on the fire behaviour making the burn more intense in areas where the fern was present. A comparison between the grass and fern fire temperatures revealed consistently higher temperatures in the data loggers from the fern clump with an average of 93.5°C compared to the grass average of 71.7°C ($p < 0.05$). Plots where the ferns were present had the tallest vegetation (Table 3.2). Height was found to be statistically different between plots with grass and fern ($p < 0.05$). Plots with ferns on average had vegetation twice as tall as grass (Table 3.2), therefore ferns contributed to a higher flame height than grass, contributing to a more effective burn where present. Large fern clumps reached higher temperatures consistently with less variation than smaller sized clumps. The medium sized clumps reached high temperatures with a few clumps having cooler temperatures. Small sized fern clumps had the coolest temperatures ranging from 60 °C to 110 °C (Fig. 3.11).

Table 3.2: Descriptive statistics of the vegetation height from the combined wetlands

Vegetation	Number of samples	Mean Height (cm)	Std. Deviation	Std. Error Mean
Ferns	97	44.02	15.85	1.61
Grass	103	27.18	10.32	1.02

Table 3.3: Ground level temperature reached by fern clumps of different size classes

Fern Clump Size	Temperature		
Large	126	126	125
Medium	125	92	77
Small	56	67	110

3.4 Discussion

3.4.1 Species composition

Long term ecological research has revealed that the legacies of historic land-use activities continue to influence the long-term composition, structure, and function of ecosystems for decades and centuries after the activity has ceased (Wallington *et al*., 2005) as is the case in Z34 with more alien species and trees than Z49. Species composition of Z49 had more characteristics of wetland species. The undisturbed wetland managed to retain some of its resilience to change as it was characterised more by wetland species compared to Z34 which had areas with vegetation characteristics of wet disturbed environments. According to MacDougall and Turkington (2005), alien invasive species are generally indicators of disturbance.

The vegetation of a wetland can be used to infer the level of wetness of the wetland as different species can tolerate certain levels of inundation, thus implying that the soil in Z49 soil is saturated more than Z34. The hydrological regime of a wetland is the major driving force that constitutes the overall composition, structure and functional diversity of a wetland (Mitsch and Gosselink, 2000). This is likely why Z49, though it has never been burned in the 25 years of the current forest management, has maintained its herbaceous wetland vegetation, and there is a lack of trees in the middle of the wetland, where conditions are wettest.

After the fire, species composition of the wetlands became even more dissimilar, with very little overlap of species. The two wetlands responded well to the fire as the fire favoured grass and sedge species, reducing alien species and tree seedlings with the exception of *Solanum mauritianum* in Z49 increasing in abundance after the fire. The effect of fire on alien species is specifically important as fire sometimes promotes alien species by prompting recruitment and can open up gaps which the alien species can fill. It is important to discover which species require manual removal versus those that fire can control. There is less variation in species composition in the sites after the fire, particularly in Z34. In Z39 similar species congregated closer together. The first 20m, before and after the fire, in both wetlands, still consists mainly of the fern species and forbs, though sedges emerged after the fire 10m into the wetlands in Z49. The difference in species composition as the distance into the wetland (level of wetness) increases becomes less evident after the fire. Species diversity for both wetlands was slightly lower after the fire due to the fire reducing the density of the alien forbs and trees.

Overall, the short term effect of fire on species composition of the two wetland sites was not substantially different. There were no major changes in the species composition of the herbaceous layer before and after the fire, except for a few *Cyperus* species after the fire and lower density of trees. Only long term studies could reveal effect of fire frequency on wetland species composition. The environmental variables measured, specifically fire occurrence and conversion into plantation, had a significant effect on the species composition. Clark and Wilson, 2001 found that fire promoted certain species over others, while other studies concludes that fire has a minor effect on species composition (Titshall *et al*., 2000; Heinl *et al*., 2007). It seems as though, over time, fire could promote certain species such as the *Cyperus* species at the detriment of alien forbs, this though needs further investigation.

3.4.2 Vegetation structure

As in the many studies of vegetation and fire, the results of this study indicates that fire has an effect on vegetation structure (Clark and Wilson, 2001; Uys *et al.*, 2004; Keeley and Rundel, 2005; Sankaran *et al.*, 2005; Weigand *et al.*, 2006; Heinl *et al.*, 2007; Martin and Kirkman, 2009; de Villiers and O'Connor, 2010). Fire had a great influence on woody plant structure, particularly reducing sapling abundance in both of the wetlands. In Z34, fire had the greatest influence on tree density suggesting that fire in this ecosystem is especially important for preventing woody plant invasion in historically disturbed wetlands which were once converted to plantation. Areas where water availability is sufficient to support forest, consumer controls/disturbances such as fire and grazing are required to maintain grasslands (Bond and Keeley, 2005; Sankaran *et al.*, 2005). Fire substantially affected *Macaranga capensis* in both wetlands. *Macaranga capensis,* a swamp forest species, is the main tree species in the transformed herbaceous wetlands which have now shifted to forest, highlighting the role of fire in these wetlands in maintaining low tree density and prevent the shift from herbaceous wetland to forest.

The high combustion efficiency in the Z34 wetland site contributed to the reduced tree density in this wetland, especially of saplings with 53% reduction in density. Fire causes major demographic bottlenecks by reducing seedling establishment and preventing saplings from emerging from the ‘fire trap’, the flame zone produced by grass fires (Higgins *et al.*, 2000; Bond and Keeley, 2005). *Halleria lucida* and *Trema orientalis,* which are pioneer forest species, were found in large numbers in the Z34 site and fire did not substantially reduce the density of these species. *Halleria lucida* was one of the forest pioneer species found in patches of forest species shifting toward forest on moist areas of the Drakensburg (de Villiers and O’Connor, 2010). It could therefore be useful to manually remove the seedlings of these species as fire had no effect on the seedlings of these tree species.

In Z49, though the fire had a low combustion efficiency, fire still had an influence on the average height of the trees that burned. This was through the increased flame height provided by the ferns. Though fire intensity calculations could not be made for Z49 we can deduce that the reason there was no significant difference in tree density before and after the fire in this wetland was the low fire intensity as a result of the inefficient combustion of the vegetation reducing the rate of spread of the fire. Though the average moisture content of the vegetation in this wetland was less than that of Z34, a low intensity fire was possible in Z49. This wetland’s species composition could be the reason for the patchy burn. It could be inferred from the species richness and type of species in Z34 that this wetland has greater biomass which contributed to higher fire intensities. These wetlands were characterised by different grass species, some species burn better than others depending on their physiologies (Z34 was characterised by taller dense and tufted species such as *Ischaemum fasciculatum* compared to the short sparse *Leersia hexandra* in Z49).

It was hypothesized that ferns would play a significant role in altering fire behaviour by suppressing fire as they remained vigorous longer than the grass. However, the results indicate otherwise as the ferns increased fire intensity. The hypothesis stating that the ferns would not have an influence on fire behaviour can be rejected as ferns produced the highest temperatures especially in larger clumps. Though the ferns had higher moisture content than grass, they reached higher temperatures than grass. The ferns, due to their height, are inferred to produced higher flame than the grass, indicating that to reduce tree density in wetlands it is especially important to burn when there are ferns present as it will create burns with high fire intensities and flame height.

The greatest requirement for high fire intensity is in the outer 20m of the wetland, where the level of invasion by trees tend to be highest; fortunately this is where most of the ferns are in the wetland. High intensity fires would prevent further spread of these invaders into the wetlands. In Fig. 3.5 we can already see this happening as all the invading alien forb species which were found in the first 20m of the wetland in Fig. 3.4 were eradicated after the fire which also reduced the density of alien invading tree species. These results suggest that if wetlands are invaded by pioneer species such as *Halleria lucida* and *Trema orientalis* beyond the areas occupied by ferns then fire is likely to be less efficient in reducing tree density. Limiting their density may require frequent fire as these two species mostly recoppiced. With prolonged periods of fire suppression, it is likely that these tree species are outcompeted by *Macaranga capensis* (the dominant and most prevalent tree species in this ecosystem) as the wetland becomes wooded which then naturally limits fire. According to Bond and Keeley (2005), once ecosystems that naturally burn experience long periods of fire suppression, these ecosystems undergo major shifts in structure and function. This occurs through increased tree density, major losses in the herbaceous understory and species diversity. From the previous chapter we know that this is the observed trend as well in this ecosystem, with fire being the limiting control of increased tree density in the long term. This study reveals a similar trend, where fire is able to reduce tree density in the short term.

3.5 Conclusion

Herbaceous systems in South Africa, including wetlands, evolved under periodic fire regimes. There have been many studies focused on the effect of fire grassland and savannah ecosystems, yet only a few have targeted wetlands. The few studies carried out on wetland burning have returned ambiguous results on its effect on vegetation. This ambiguity has made it difficult to recommend an appropriate management strategy for wetlands, hence the need for this study.

This study, though it was on a burn experiment with a single fire event, like other studies such as Titshall *et al.*, 2000; Clark and Wilson, 2001; Uys *et al.*, 2004, Hienl *et al.*, 2007 investigating fire and vegetation, has revealed that fire has a greater influence on species woody plant structure than it does on the herbaceous layer. This is especially true in herbaceous dominated ecosystems where the vegetation is generally fire-tolerant. Fire is an important control (secondary control) of species structure, without which, herbaceous species composition shifts to woody species composition shift to wooded states where the vegetation itself excludes fire. Prescribed burning has proved to be an important management tool world-wide in preventing regimes shifts, and is evident as well in this study, thus it is important to apply fire to the wetlands in this ecosystem.

Ferns which were thought to suppress fire contributed to hotter burns which can be positive for the herbaceous components of wetlands as prescribed fire is only applied on cool days in plantation forests. The presence of ferns therefore would contribute to higher fire intensities, which are needed to reduce tree densities without putting the neighbouring plantations at risk. Fire is especially important in wetlands which were converted to plantation in the past (disturbed). The results of the burning experiment demonstrate that pretreatment of ferns (to induce the desiccation of ferns for better fuel combustion) with herbicide prior to burning might not be necessary for effective combustion.

Though there are limitations to this study, specifically dealing with the timing of re-sampling which took place before a full growing season, the findings of the study emphasize the regular use of fire in this ecosystem to maintain the herbaceous layer and prevent the shift from herbaceous wetland into forest. Only high intensity fires could possibly push the woody vegetation back into herbaceous vegetation. This would need to be followed by some mechanical or herbicide treatment for the more fire-tolerant species such as *Halleria lucida* and *Trema orientalis*. Studies in the USA on the restoration of small wetlands have concluded that removal of woody species is required to restore the historic herbaceous vegetation of wetlands. This will allow future fires to burn and maintain the herbaceous vegetation. Once the herbaceous regime-positive feedback system is re-established, regular prescribed fire should be able to maintain the herbaceous vegetation with regular monitoring of *Macaranga capensis* seedlings. At this point mechanical or herbicide measures may no longer be required depending on the recruitment rate of the pioneer tree species.

The differences in disturbance history and the lack of replication of treatment sites is a limitation to this study. However, in terms of informing management, it is useful that the study included wetlands with large differences in disturbance history. Despite the large differences in disturbance history between the two wetlands, the positive effect of fire in controlling invasive woody plants was clearly demonstrated at both sites.

A single fire event in the two wetlands is an additional limitation of the study, as the value of assessing the accumulated effect of a sequence of fires over some years is lost. The two wetlands in the study had not been burnt for several years before the fire, and outcomes such as the dramatic increase in *Solanum mauritianum* seedlings in Z49 following the burn could in part be a function of this and might well decline following a series of regular burns. Thus, it is recommended that this study be continued to additional fires.

The inability to burn the number of wetlands and treatments as planned is a result in itself. It demonstrates the difficulty of burning these wetlands as the conditions for fire are generally either unfavourable or dangerous. This is a combination of weather and seasonality issues which cannot be controlled by the managers and therefore needs to be taken into consideration when developing a management plan for these wetlands.

Chapter 4
Discussion, Conclusions and Recommendations

4.1 Discussion and Conclusions

There is uncertainty that is facing water management planners with regards to future water availability and demand. The imminent threat of climate change and the likely hydrological effects are adding to this uncertainty (Middlekoop *et al.*, 2001). The predicted climate changes include a global increase in temperature and consequently, an increase in floods and droughts in certain areas of the world (Hannah *et al.*, 2002, Joubert, 2008). This is expected to lead to a more erratic regional water cycle with changes in the amount of water a region receives and the rates of evapotranspiration (Middlekoop *et al.*, 2001; Hannah *et al.*, 2002).

Global atmospheric carbon dioxide levels are also predicted to increase and subsequently will favour woody plants over herbaceous plants as carbon dioxide can influence the growth rate of juvenile plants, thereby affecting tree recruitment and the conversion of open savannas to woodlands (Bond and Midgley, 2000; Dukes, 2000; Woodward, 2002; Bond and Midgley, 2012). According to Bond and Midgley (2012), the changes of grasslands, open mesic and humid savannas to woodlands and forests are consistent with experimental and simulation studies of carbon dioxide effects. These conversions of largely herbaceous systems into wooded systems will ultimately affect the water availability of a region through increased rates of evapo-transpiration (Le Maitre *et al.*, 1999; Dye *et al.*, 2008) and therefore the management of water systems. The changes in the water cycle associated with climate change will be very detrimental to the development of South Africa, which is already a water scarce country. A lot of South Africa's industry and agriculture relies on water, which contributes to water being a limiting factor for development (Sylvain, 2002). Any changes therefore in the water supply could have major implications in most sectors of society and the economy.

Water is a very important component of the natural world and human survival but water sources (river systems and wetlands) are becoming increasingly degraded and less functional, which is particularly concerning with the looming threat of climate change upon us. This study's particular concern lies in the degradation of wetlands through the increase of woody species into wetlands, as they invade wetlands which are predominantly herbaceous. Woody species generally use more water than herbaceous species (Richardson and van Wilgen, 2004;

Dye *et al.*, 2008) and this impacts wetland function. In moister savannas and grasslands woody species are influenced significantly by fire, and fire is consequently used widely as a means of reducing woody plant density. However, in wetlands there is uncertainty about the effectiveness of fire in combating woody plant encroachment and the general impact of fire. The aim of the study, therefore, was to determine the influence of fire on wetland vegetation structure and composition.

To do this, a fire and disturbance history of the Kwambonambi wetlands was compiled. It was determined that these wetlands differ greatly in their fire and disturbance history. A large proportion of the wetlands in this area were once converted into plantation forest. Those that were not planted to plantation were generally the wettest wetland areas, which were unsuitable for tree plantations. A large number of these wetlands have not been burned. A number of the wetlands have experienced accidental fires with some wetlands being burned as part of the prescribed burning for reduction of fire risk between plantations. Once the survey of fire and disturbance history was done, a comparison could be made of the long term changes in vegetation structure using remote sensing and relate it to the fire and disturbance history.

The Kwambonambi landscape has undergone large amounts of transformation, with 92.4% of the landscape being altered, indicating a great degree of ecosystem change and habitat destruction. According to Chapin *et al.* (2000) and Fanan *et al.* (2011), significant amounts of change to the earth's surface is attributed to anthropogenic factors such as land cover change in the form of afforestation, while natural factors play a significant but minor role in this change. This is evident in this landscape where the large scale transformation in land cover has contributed to changes in the natural (not human altered) ecosystems. The Kwambonambi landscape has been converted from a herbaceous vegetation dominated landscape to a landscape dominated by plantation forest and indigenous forest. This is a major shift in ecosystem function as the main change is from a mainly herbaceous ecosystem which uses less water to a forested ecosystem which uses substantially more water (Richardson and van Wilgen, 2004; Dye *et al.*, 2008), and as a result this landscape is significantly drier. This dryness is due to deep rooting, ever-green forestry trees having high water interception and higher evapotranspiration rates (1100mm or more) compared to grass and shrubs which have evapotranspiration rates of approximately 700mm (Dye *et al.*, 2008).

This drying of the landscape has both hydrological and ecological effects on the wetlands. A systems approach to looking at change suggests that one change in the system could possibly induce a change (positive or negative) in another part of the system. Wetlands get temporarily, seasonally or permanently flooded/saturated, a disturbance which maintains and dictates how the system functions. The depth and duration of flooded/saturated conditions is attributed to be the major environmental variable contributing to the structural and functional diversity of wetlands (Kirkman, 1995; Mitsch and Gosselink, 2000; Turner *et al.*, 2003). Areas of different levels of wetness have different vegetation species composition, depending on a species ability to withstand long periods of inundation/saturation. Any alteration in the hydrological regime causes change in the system. Kirkman (1992) reported that the lack of persistent inundated periods and persistent dry periods contributed to the encroaching of tree species into herbaceous wetlands. This is the same result obtained in this study. Plantation forests can reduce water availability in small wetlands by up to 40% due to high water interception and evapotranspiration rates (Helmschrot, 2005). It is hypothesised that this persistent drying of the landscape has contributed to the encroaching of tree species into the wetlands and the lack of a persistent fire regime and fire suppression allowed for the system to shift into an alternate forest state.

The main reason for the change in structure of the Kwambonambi wetlands is therefore attributed to the lack of fire as part of the management of the wetlands. According to Henkel *et al*. (1936) the Kwambonambi area experienced regular fires, which was noted to be of great ecological importance in hindering the expansion of forest which was confined to locations protected from fire. Results from chapter 2 highlight the role fire has had in maintaining short herbaceous vegetation and concurs with this statement made by Henkel and colleagues.

The role of fire becomes of greater significance in wetlands which were once converted into plantation. In the sample wetlands in this study, all the wetlands which were once converted into plantation and have not been burned by management have become forest whereas wetlands which have experienced fire have become woodlands (characterised by a majority of trees with open herbaceous areas). The only wetland which has maintained its herbaceous structure has been burned multiple times and was not converted into plantation. This concurs with other studies of wetland vegetation and fire, where the active use of fire has led to a decrease in woody tree species in wetlands (Clark and Wilson, 2001; Heinl *et al.*, 2007;

Martin and Kirkman, 2009) and has restored the herbaceous vegetation-fire feedback mechanism (Martin and Kirkman, 2009).

On closer inspection of the effect of disturbance on the wetland composition, results show that wetlands differ compositionally because of disturbance. Using canonical correspondence analysis, the two sample wetlands separated out with no overlap in species composition, with disturbance -both fire and conversion into plantation- being the driving variables. There are slight changes compositionally after the fire, specifically, the fire minimized the occurrence of alien invasive species and promoted the occurrence of wetland herbaceous species. These wetlands differ significantly in their histories. One of the wetlands experienced both forms of disturbance with the other having experienced neither of these disturbances.

This study has two limitations, the sample size of the wetlands which prevented comparing the effect of varying degrees of disturbances on the wetlands and limited replication with results obtained from a single fire event. Regardless of the limitation, the results obtained from the study are still useful. Statistical results reveal that fire is important in the maintenance of herbaceous wetland, confirming the observation from chapter 2 where Z42, being the only wetland to be managed with prescribed fire, remained herbaceous. Tree density in the disturbed wetland, before and after the fire, was significantly different with tree density being 31% lower after the fire. This highlights the importance of fire on disturbed wetlands as hypothesised from the result of chapter 2. On the undisturbed wetland, fire had a statistical difference on the average height of the trees, reducing the average height of trees after the fire from 1.8m to 0.5m. Table 2.3 shows that most of the undisturbed wetlands had been invaded by trees but they had not become closed forests, but remained as either low sparse or open woodlands. This suggests that in undisturbed wetlands, where the topo-edaphic conditions were not disturbed previously (specifically relating to the conversion into plantation and clearfelling), the wetlands are able to maintain some resilience to change into an alternate state, slowing down the process of a system change.

The wetlands in this study site have mainly changed from herbaceous wetlands into a “herbaceous, fern species mix”; “herbaceous, fern, tree species mix” and indigenous forest. The shift from herbaceous wetland to forest was thought to happen by means of succession from the invasion of fern into the wetland, which then suppressed fire occurrence and spread, simultaneously outcompeting herbaceous species and providing trees the right conditions to thrive. *Pteridium aquilinum* is an invasive fern which according to Adie *et al.* (2011), aids in the transformation of grassland to forest in periods of long fire suppression by providing establishment opportunities for resprouting early-successional forest species. This then directs plant community development down alternative, and irreversible, successional pathways from grassland to forest. The ferns in this case study, particularly *Stenochlaena tenuifolia*, appear to play a similar pivotal role in aiding the development of forest during periods of fire suppression. This role is diminished though if the wetlands experience frequent fire, as the results of the study show, in areas where the fern is present, fire temperatures and flame height were at their highest. This then suggests that if fire was frequently applied to these wetlands, the occurrence of ferns in them could in fact contribute to higher fire intensities than initially hypothesised.

Due to limiting factors unforeseen and uncontrollable by the researcher the objective to compare the effects of different fire regimes in the successful management of invasive woody species could not be successfully done. This is because the study site is located in a sub-tropical area which has high mean annual precipitation of 1380mm and the winter months on average receive 232mm of rain (South African Weather Service data, 2012), and thus rainfall prevented the burning of more wetlands. The inability to burn the initial sample size of five wetlands demonstrates the difficulty of burning these wetlands. This was due to a combination of weather and seasonality issues which cannot be controlled and therefore need to be taken into consideration when developing a management plan for these wetlands. Though certain limitations exist within this study, there was enough evidence from the study to demonstrate the ecological significance of fire in limiting the invasion of woody plant species into the wetlands. The aim of the study is therefore met which was to examine the influence of fire on wetland vegetation structure and composition of the Kwambonambi wetlands.

Wetlands provide many important services to human society, but at the same time may be ecologically sensitive. Turner *et al.* (2003) notes that there are more than fifty definitions of what constitutes a wetland with no universally agreed on classification of wetland types. There needs to be better understanding of the functioning (the interaction among wetland hydrology, geomorphology, saturated soil and vegetation) of these wetlands which will inform their management. With the formation of the Ramsar Convention, more attention has been directed towards the formulation and operation of sustainable management strategies for wetlands. These sustainable management strategies can only happen with the recognition of the importance of a holistic/systems approach to studying the environment-as wetland degradation generally goes beyond drainage basin boundaries. This study tries to understand the effect of fire on wetland vegetation in a context of wetland changes and losses at a small spatial and temporal scale for informing management on the best use of fire on wetlands. The appropriate management strategies maintains the characteristics, processes and structure of wetlands which in turn affects wetland functioning of a wetland, which is key to the continuation of provisioning of goods and services.

In order to develop meaningful management strategies, there needs to be a good understanding of the problem and the underlying processes contributing to the degradation and loss of the system you are trying to manage, in this case it is wetlands. The main drivers of the vegetation structure in this landscape are the land use/land cover change in the form of large scale plantation forestry coupled with fire suppression. The large scale plantation forestry in the landscape has led to the drying of the landscape (which affects the hydrology of the wetlands) and therefore levels of soil saturation have decreased. Simultaneously, plantation forests are fire suppression areas to avoid losses in trees. These factors have allowed forest species such as the fern *Staenoclina tenuifolia* and *Macaranga capensis* to invade the wetland areas. Over time, the combination of fire suppression and drying encourages the establishment of woody seedlings, turning wetlands into swamp forests/woodlands. On a localized scale, a third significant factor in this change is disturbance in the form of directly converting some wetlands into plantation forest. The results from the land cover change analysis show that this regime shift form herbaceous wetland to forest is more evident in wetlands which were once converted into plantation forest with insufficient woody plant species control to accompany the withdrawal of plantation. Z49 and the other few wetlands which have maintained their herbaceous structure following the withdrawal of plantation from the wetlands are those maintained with fire as a management strategy.

4.2 Recommendations

Once the problem and the underlying processes contributing to the degradation of the system (wetlands in this case) are better understood, recommendations could be made which are scientifically sound and practical for management, especially these novel ecosystems (Fig 4.1). Novel ecosystems are 'emerging ecosystems' where new species combinations due to degradation and invasion of natural or semi-natural system as a direct or indirect implication of human action, with the potential to change ecosystem functioning (Hobbs *et al.*, 2006). The results of this study suggest that burning the wetlands biennially (as Z42), during the dry season, has been able to enhance the resilience of these wetlands to invasion by swamp forest species. Commonly, during drier periods and decreased duration of inundation, woody plants are able to more readily establish in wetland areas (Kirkman, 1995; Martin and Kirkman, 2009). This highlights the need for an active fire regime particularly as the wetlands are becoming drier. Wetlands once converted into plantation also require particular attention as most of these wetlands have already shifted into a forest state. *Trema orientalis* which is a forest pioneer tree, common in disturbed, moist soils and *Halleria lucida* another pioneer tree species were common in the wetlands associated with conversion to plantation and subsequent withdrawal.

As shown in this study, it may be difficult to burn some wetlands, due to weather and seasonal variations (especially with the unpredictable nature of the weather changes brought about by a changing climate), but the effort needs to be made to burn. This is especially true in areas invaded by the fern where if it were just grass the burn might not be successful, but the ferns will probably aid in the spread of the fire and increase fire intensity.

Another intervention would be to expand the buffer around the wetlands that have maintained their integrity. The buffer zones are areas created around the wetlands to limit the negative impacts of the plantation on the wetlands-particularly the desiccation. This is expected to increase the amount of water in the wetlands which will improve wetland hydrology and ultimately improve the wetlands resilience. A wider buffer would also allow greater latitude for controlled burning of the wetland without unduly threatening the adjacent plantation.

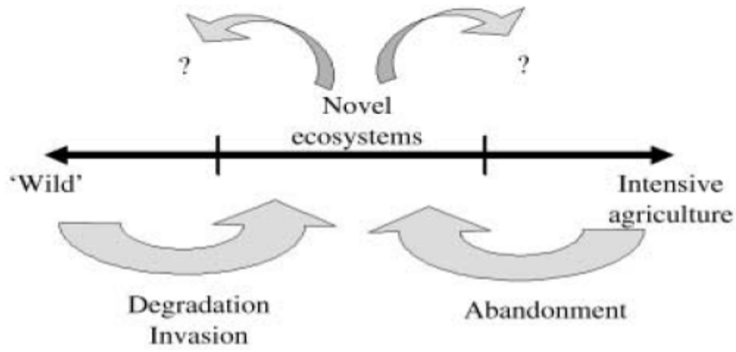


Figure 4.1: Novel ecosystems arise either from degradation and invasion of 'wild' or natural/semi-natural systems or form the abandonment of intensively managed systems (Hobbs et al., 2006).

The study had specific research objectives (given in chapter 1) which were conceptualized and developed in response to specific management issues, in particular, herbaceous wetlands shifting to forest. This study has yielded useful insights which might help management prevent the vegetation shift happening in the wetlands. It is therefore important to relate this back to the management of plantations. A workshop, held with various foresters in the area, was recommended to co-develop a wetland management strategy that will be both practical for the forester and ecologically sound. Pahl-Wostl *et al.*, 2007 calls this the "science of working together". In this workshop, it is recommended that the research (fire and wetlands) findings be communicated back to plantation forest managers, and the practical management implications of the findings be explored with the management staff who should assist with identifying some specific actions (and key indicators for monitoring the outcomes of the actions) with regard to burning of the wetlands. This would hopefully lead to a relationship where science and management rely on and learn from each other with open relations, which in due course will lead to better wetland management.

As per the recommendation, a workshop (Workshop report is attached as appendix 2) was held with foresters and environmental managers in the area. This workshop was very productive, and everyone agreed that these wetlands need to be burned more than they are currently, and specific management targets were set. With the aid of the land cover maps, priority areas which were viable and would yield the greatest result with added management effort were identified. The burn frequency which would be ecologically sound and practical for managers was discussed at length, taking into consideration weather conditions of the area, the Fire Danger Index and the disturbance history of the wetlands, and was agreed on. The workshop attendees emphasized the importance of continuity which highlighted the need for a management plan and monitoring system. Key partnerships were formed in the workshop as everyone realised the importance of working together towards a similar goal, and in this case the prevention of a regime shift in the herbaceous wetlands.

Reversing the forest state back to herbaceous wetlands would require mechanical clearing and active fire to enhance and maintain the integrity of the wetlands. Removal of woody forest species from wetlands can restore the herbaceous vegetation-fire feedback mechanism and ultimately restore the system back to an herbaceous state (Martin and Kirkman, 2009). Though clearing established forest is typically a very expensive endeavour, it is not impossible to try and restore these wetlands back to their herbaceous state. This landscape changed from a water provisioning, grazing, biodiversity maintenance and provisioning landscape into a landscape which is biodiversity poor, mainly consisting of plantation forest and indigenous forest which is mainly *Macaranga capensis* dominated. Forest clearing from the wetlands would be a significant commitment from the forestry company into the water security of the area and the biodiversity maintenance of some of the critically endangered ecosystem.

The occurrence of swamp forest is clear from the historic map of the landscape, it is therefore important to maintain these areas. The conclusion that fire controls woody plant invasion, elicits the question of why swamp forests exist at all in this system? We hypothesise that though the topography is gently undulating, not all parts of the landscape are equally susceptible to fire. Some of the low lying areas, particularly those that intersect the regional water table, having prolonged surface water, which could potentially act to suppress fires in these localized areas, thereby allowing for the persistence of swamp forest. The recommendation is not too clear all swamp forest from the landscape, but a recommendation of rehabilitation of the historically herbaceous areas. This alludes to a research gap in the knowledge of the occurrence of swamp forest. The recommendation of this study would be to further investigate this question with hydro-geomorphic studies.

Though this study has yielded some useful insights, there are obvious research gaps which need to be addressed to further the knowledge of the dynamics of the wetlands in the Kwambonambi area (and the greater Maputaland coastal area). Another recommendation would be to expand the research, both time series and in geographic area. The expansion of the geographic area is to compare plantation areas versus non-plantation areas. This is expected to contribute further insights into the dynamics of the wetlands in this region and possibly identify possible drivers of change that the scope of this research couldn't. The greater region consists of timber forestry, urban and rural areas; herbaceous wetlands may be shifting into forest/woodland even in non-plantation areas and if so global drivers such as the change in carbon dioxide concentrations may be playing an even greater role than hypothesised by the study. Expanding the time series data (particularly shorter periods in the last 30 years which would capture vast changes in land cover/land use but also the drastic changes in the carbon dioxide concentrations) would help identify some of the more social (such as changes in management regimes) and global drivers of change. A systems approach to investigating these shifts could possibly identify other key drivers which were missed by this study.

Lastly, the long term effects of burning on wetland species composition cannot be answered in a short term Masters study, therefore as the foresters continue to burn and monitor the wetland changes, the continuity of the scientific study parallel to this would produce results similar to long term grassland fire trials. This would be especially important as climate change predictions point to further shifts from herbaceous biomes to wooded biomes.

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Appendices

Appendix 1 : Species List

Sen Poly- Senecio polyanthemoides

Cent asiat- Centella asiatica

Isch fas- Ischaemum fasciculatum

Andro fest- Andropogon festuciformis

Dact aus- Dactyloctenium australe

Pani parv- Panicum parvifolium

Hall luc- Halleria lucida

Leers hex- Leersia hexandra

Pan hym- Panicum hymeniochilum

Thel inte- Thelypteris interrupta

Cyp sen- Cyperus sensilis

Erios spp- Eriosema spp.

Con canad- Conyza canadensis

Con bon- Conyza bonariensis

Mac cape- Macaranga capensis

Scle spp- Sclera spp.

Trem- Trema orientalis

Smil anc– Smilax anceps

Comp spp- Composit spp.

Lant cam- Lantana camara

Psi catt- Psidium cattleianum

Sol maur- Solanum mauritianum

Doda spp- Doda spp.

Pasp spp- Paspalum spp.

Erag pla- Eragrostis plana

Pyc poly- Pycreus polystachyos

Hel coop- Helichrysum cooperi

Fern spp1-Nephrolepis biserrata

Stae ten- Stenochlaena tenuifolia

Pter aqui- Pteridium aquilinum

Phoe rec- Phoenix reclinata

Gom fle- Gomphocarpus flexuosa

Heli long- Helichrysum longifolium

Pani spp- Panicum spp.

Cyp lat- Cyperus latifolius

Hemar alt- Hemarthria altissima

Erag inam- Eragrostis inamoena

Cyp sphae- Cyperus sphaerocephala

Poly pleb- Polygonum plebeium

Aca spp

Cyp spp

Forb 2

Forb 5

Forb 6

Forb 7

Forb 8

Forb 9

Forb 10

Forb 11

Forb 3

Forb 12

Forb 4

Forb 1

Tree Species

Mc- Macaranga capensis

Sc- Syzygium cordatum

Pg- Psidium guajava

Bm- Bridelia micrantha

Hl- Halleria lucida

To- Trema orientalis

Lc- Lantana camara

Sm- Solanum mauritianum

Pr- Phoenix reclinata

Lo- Ludwigia octovalvis

Ft- Ficus trichopoda

Appendix 2: The Mondi Wetlands Programme's Fire Workshop Report

Mondi Wetlands Programme

Forestry, Fire and Herbaceous Wetlands in Kwambonambi: Engaging management with recent research findings

Deliverable 1: Key findings of the research and outcomes of a workshop with managers

September 2013

Linda Luvuno, Donovan Kotze and Damian Walters

1. Background and objectives of the workshop

According to Henkel *et al*. (1936) the Kwambonambi area experienced regular fires, and most of the Kwambonambi wetlands are therefore naturally dominated by herbaceous vegetation which is well adapted to fire. These wetlands support a rich diversity of herbaceous plant species, including the only known wild population of the critically endangered *Kniphofia leucocephala* confined to a single wetland, Langepan, as well as other Red Listed species such as *Asclepias gordon-grayae,* and *Restio zuluensis*. The rich fire-dependent herbaceous flora suggests strongly that even before the earliest human inhabitants of the area started influencing fire, the Kwambonambi wetlands evolved under natural periodic fires.

However, in the last four decades in particular, the area has been subject to very high levels of transformation to tree plantations and human settlements, leading to the reduced incidence of fire, which in turn has resulted in extensive encroachment of the herbaceous wetlands by woody plants, notably *Macaranga capensis*. Henkel et al. (1936) also noted that while fires prevent the expansion of forest, they normally are unable to penetrate or burn back once the forest has become established. Management choices, particularly with respect to fire, have potentially profound consequences for these wetlands (Figure 1).

A wetland area previously planted to timber and not burnt following withdrawal of the timber: now the vegetation is dominated by indigenous trees, mainly *Macaranga capensis,* an understory of the fern *Staenoclina tenuifolia* and very few other species (i.e. an understory very similar to that occurring beneath the tree plantations).

A wetland area previously planted to timber and regularly burnt following withdrawal of the timber: mixed fern and short sedge/grass vegetation has become established. Although now dominated by sedges, notably *Scleria sobolifera*, woody saplings are common and will need to be controlled if the area is to be maintained as herbaceous vegetation.

A wetland area which has been regularly burnt and not previously planted to timber: short sedge/grass vegetation, supporting *Andropogon festuciformis*, *Xyris capensis* and a very rich diversity of other herbaceous plant species have been maintained.

Figure 1: Different potential states, as influenced by fire regime and past disturbance, of Kwambonambi wetlands which were historically herbaceous. It is hoped that with time the mixed fern and short sedge/grass vegetation would develop into sedge/grass vegetation, supporting a rich diversity of herbaceous plant species.

This highlights the need for understanding the interaction of fire and the plants in these wetlands. In response to this need, an MSc thesis on the effect of fire on wetland vegetation structure and composition was undertaken and is very soon to be submitted. The thesis has yielded important results of direct relevance to management.

A workshop was conducted on 17 September 2013 in which the results of the MSc were shared with management staff and other key role-players in such a way as to add to the knowledge generated in the MSc and to promote the incorporation of new knowledge into management practice.

The specific objectives for the workshop were as follows:

1. Provide an opportunity for the researcher, Linda Luvuno, to report back on the findings of her MSc project on fire in the wetlands of Kwambonambi to Mondi managers.

2. Through discussion and a field visit (Figure 2) explore, with the management staff, the practical management implications of the findings and other personal observations and experiences of managers.

3. Assist Mondi managers to identify some specific actions (and key indicators for monitoring the outcomes of the actions) with regard to burning of the Kwambonambi wetlands, informed by objectives 1 and 2.

The workshop was attended by six Mondi and SiyaQhubeka Forests (SQF) foresters, three Mondi Environmental Officers, the Fire Protection Officer for the Zululand Fire Protection Agency (ZFPA), a locally-based ecologist who provides Mondi with ecological advice and an ecologist or restoration ecologist from Richards Bay Minerals.

Figure 2: Participants in the workshop at the field site, Compartment Z34, comprising a central herbaceous area surrounded by mixed fern, woody and herbaceous vegetation.

2. Objectives and key findings of the research

2.1. Aim:

The aim of this study was to examine the influence of fire on wetland vegetation structure and composition of the Kwambonambi wetlands, South Africa.

2.2. Objectives:

- To compile a fire and disturbance history of the Kwambonambi wetlands.
- To compare the long term changes in vegetation structure using remote sensing and relate it to the fire history.
- To compare the differences in wetland vegetation structure and composition in wetlands with differing fire history.
- To compare the effects different fire regimes in the successful management of invasive woody species.

2.3. Results:

As this result section is a replica of the results presented in the thesis, the result section here in the report has been removed.

3. Outcomes of the workshop

3.1 Some key management question raised and responses

At what frequency do you need to burn?

This is likely to depend strongly on the disturbance history of the site. If the objective is to control invading woody plants (e.g. *Macaraga capensis*) then areas which were historically under plantation and subsequently withdrawn generally require a higher fire frequency than areas which have never been under plantation. Furthermore, the greatest need for a high burning frequency is immediately after withdrawal of the plantations. To highlight this point, it was described how Rudolph Muller implemented a burn for three consecutive years immediately after withdrawal of plantations from "Langepan 2 wetland", and this was very effective in promoting herbaceous vegetation.

Under what Fire Danger Index (FDI) code is it acceptable to burn?

Generally the higher the FDI code, the more effective is the fire in controlling woody plants, but the greater is the risk of a runaway fire. A key question therefore is how "high" would management be prepared to go to control invasive plants but which was still within an acceptable level of risk. The clear response from the foresters and the Fire Protection

Officer was that and FDI Code yellow would be acceptable provided the necessary precautions had been taken but a Code orange would be too high.

In addition to the direct risk, a further danger of burning when the FDI index is high is that this is generally the time when unplanned fires occur. During such times there is a need to be ready to respond rapidly to any unplanned fires, which would not be possible if already busy with a planned fire, which cannot immediately be abandoned to attend to the unplanned fire.

What about impacts of fire on swamp forest?

Would the proposed burning causing loss of swamp forest, and how systematic and well considered was the process being suggested? In response it was noted that areas identified for promoting herbaceous vegetation and controlling woody plants were well informed in terms of where the swamp forests historically occurred, and there was certainly no intention of converting any of the original swamp forests to herbaceous wetlands. Only areas recently invaded by trees are being targeted. It was also highlighted how the cumulative loss of herbaceous wetland is considerably higher for herbaceous wetlands than swamp forests.

What about grazing?

It was agreed that the wetlands would have been naturally grazed and that it is beneficial for biodiversity to have grazing in a wetland. However, heavy grazing, which significantly reduces fuel load, reduces the effectiveness of fires in controlling invasion by trees. This is given that the greater the fuel load, the higher the fire intensity and therefore the greater the potential impact on the trees.

Is it useful to aim for the 1938 situation?

There was a question about why are we going back to the 1938 situation, and is it justified to work against plant succession? In response, it is recognized that it is impossible to achieve the 1938 situation, because, for example, some wetlands have been considerably dried out by the drawdown of the regional or local shallow aquifer by plantations. Nevertheless, working within these constraints, the 1938 situation provides a useful point of reference. It is worth the effort to restore/maintain historically herbaceous wetlands given the considerable benefits to fauna and flora as well as the benefits in terms of water yield (herbaceous [sedge/grass] wetlands generally use much less water than forested wetlands). The natural situation is holding succession back and it is actually recent human-induced which has for many of the wetlands allowed succession to proceed to its forested endpoint.

Is there a need for mechanical clearing of trees?

Compartment Z34, which was visited in the field (Figure 2), was used as an example and the question posed: could this compartment be effectively burnt? The foresters answered that it could, but they also emphasized the need to cut down the trees (mainly *Macaranga capensis*) on the edge of the wetland. As shown by the findings of the MSc, taller trees are less likely to be killed by fire than shorter trees.

This emphasized that particularly where wetlands are in transition between herbaceous and woodland/forest then fire on its own will generally be inadequate to prevent woody plants becoming dominant and the herbaceous component being lost.

It was added that one need to start preparations well ahead of a scheduled burn, particularly the cutting of trees which will require time to dry out before the fire in order that they burn well.

Tony Roberts of ZFPA indicated that Working for Fire would be able to assist with cutting down of the trees, which will assist greatly!

What about the indigenous trees which tend to grow on the edge of the wetland adjacent to the plantation?

Trees on the edge adjacent to the plantation (Figure 1) are best cleared otherwise they will be a very close seed source for invasion of the herbaceous wetland area.

How can a better motivation be put forward for senior management to allocate more resources to the control of woody plants in herbaceous wetlands?

It appears that once the imminent Stewardship agreement comes into effect it is unlikely in itself to provide a strong motivation for levering greater resources. Perhaps carrying greater weight is Mondi’s responsibility to minimize its water footprint. However, in order to make this argument it would be useful to calculate, even if it fairly coarsely, the net annual volume of water lost for every hectare of herbaceous wetland which is lost to forest. The environmental manager pointed out that the removal of trees out of these wetlands is part of Mondi’s environmental and social responsibility because of the increased water use resulting from these trees.

3.2 Some key general recommendations from Tony Roberts of the Zululand Fire Protection Agency

- The stakeholder need to be involved in making decisions about the where to burn ahead of time
- The areas to burn and their extent must be mapped out.
- Managers need to understand the ecological issues around burning wetlands, taking flora and fauna into consideration
- Spring and summer burns are most likely to impact negatively on fauna and are best avoided.
- Carry out fire breaks and other preparations well ahead of the scheduled burn.
- Take measures to prevent overgrazing post-burn.

3.3 Key decisions emerging from the workshop

Prioritization

It was agreed that it is better to tackle fewer sites and to do them well rather than over-stretching and taking on too many sites. Therefore there is a need to select those wetlands which are most viable and likely to yield the greatest "bang for our buck". It was agreed that the two key criteria for prioritizing areas for frequent burning are:

- Wetlands that are already dominated by trees should be left and the focus should be on are more easily saveable areas where trees are less dominant, particularly those that are next to natural areas which have never been under plantation and which serve as useful links between exiting natural herbaceous wetland areas.

- Large and broad areas should be chosen over small or narrow areas. Large/broad areas are easier to burn and are subject to less edge effect from the adjacent plantations.

Langepan is clearly the highest priority given that it is by far the largest natural fragment of herbaceous wetland remaining. The next highest priority is what is referred to as "Langepan 2". In addition to scoring highly in relation to the above two criteria, Langepan 2 appears to be closest to Langepan in terms of its hydro-geomorphology and is therefore likely to have a relatively high likelihood of maybe supporting the species, including the Red Listed species, currently found in Langepan.

Langepan and "Langepan 2" are already in the fire plan, and Mondi SQF committed to adding an additional 60ha of wetland into their fire plan. The responsibility for identifying the additional areas based on the agreed-upon criteria lies with Lize Shaw. The responsibility for implementing the burn lies with the forester, Mbusiseni Masangu. The FPA again, pointed out that they can help but only with their conservation areas burns, which was very encouraging.

Burning frequency and timing for prioritized wetlands

The foresters pointed out that the best time to burn wetlands is when they are burning the slash in the plantation blocks after harvesting, which is every 7 years, i.e. conservation burning should be aligned with slash burning. It was agreed that for priority wetlands, at least two additional burns be included in the seven year rotational cycle.

Timing of burn was discussed at length. The general consensus was to aim for July, but with the possibility that it might go into September. In dry years, it will often be possible to burn earlier, generally in May and June but sometimes even as early as March, and burning occasionally at this time would also be acceptable.

Monitoring

Probably the most important element with respect to monitoring is to maintain good records of burning for each prioritized wetland. In this way it can easily be checked if the target number of burns has been reached for each successive seven year burning cycle. At the level of the overall estate, Kotze (2011) provides a summary for managers to track how they are performing in relation to burning of wetlands for the overall estate. It may be, for example, that initially 80% of the herbaceous wetlands in the estate were being inadequately burnt and 20% adequately burnt, while in the next cycle the situation had been improved to 40% of the herbaceous wetlands in the estate inadequately burnt and 60% adequately burnt.

In order to determine whether the outcome of burning on vegetation structure is being achieved, tree cover vs. herbaceous cover should be monitored. Fixed point photographs would provide a coarse indication of this and should be considered as the minimum requirement for monitoring. Fixed point photographs should be done annually (at the same time of year) in non-burn years and in years when a burn is scheduled three photos are required. The first before the burn, the second immediately after the fire photo and the last one should document the post fire vegetation recovery.

It was suggested also that it would be useful to know what herbaceous species to expect and to monitor if this is being achieved. The expected species are likely to vary according to the particular hydrological/soil conditions at the site (i.e. wetter sites would support different species to drier sites). Rick van Wyk, who has good local knowledge of the plant species, would be able to assist in this regard.

The issue of the importance of monitoring and continuity was highlighted, and a request was made for the research to continue beyond Linda's MSc project. MWP offered to enquire if SAEON can help with the monitoring by sampling the wetlands in order to keep track of compositional changes. The plots surveyed by Linda in 2012 could be repeated. In addition, other plots surveyed by Rick van Wyk in 2006 provide further points of reference which would be useful to repeat.

A burning management plan

The value of a management plan was emphasized in terms of continuity of management. A management plan, including burning, was developed by Rick van Wyk, but Rick added that there was scope for revising this in the light of the recent research.

Including wetlands outside of the study area

The research study area did not include the whole of Mondi SQF land, and so it was agreed that the same criteria for prioritizing would be applied on the rest of the Mondi SQF land. Lize Shaw took responsibility for carrying this out. Priority wetlands identified in this additional land will then need to be incorporated into the fire plan.

Other forestry companies in the greater Kwambonambi area also need to identify key wetland areas that can be saved. Thus, the need for collaboration and linking up with the other forestry companies in the area was also emphasized. This report from the workshop will assist in providing rationale and practical guidelines which could assist these other companies.

Identification of peatbeds

Some of the wetlands that were delineated and cleared of forestry are peatlands. Some of these are active or functional peatlands with intact hydrologies while other are no longer functioning and have been dried out despite the delineation. The dry peatlands pose a fire hazard during management burns of open areas. These systems need to be identified and included into fire management plans.

The Mondi Wetland Programmes further involvement

The Mondi Wetlands Programme has invested considerable resources in helping Mondi improve its fire management of wetland (and grasslands) on its land. There is clearly an increased recognition of the importance fire management in wetlands within both environmental support staff and foresters. This is translating into action on the ground where we see improvement in how wetlands are burnt. The MWP plays an important role in supporting improved management by providing opportunities) or spaces for reflection and learning, the recent workshop being a good example of this. It is suggested that the programme should continue to support such activities at a small scale and possibly include a monitoring support function to insure that lessons learnt during practice are not lost.

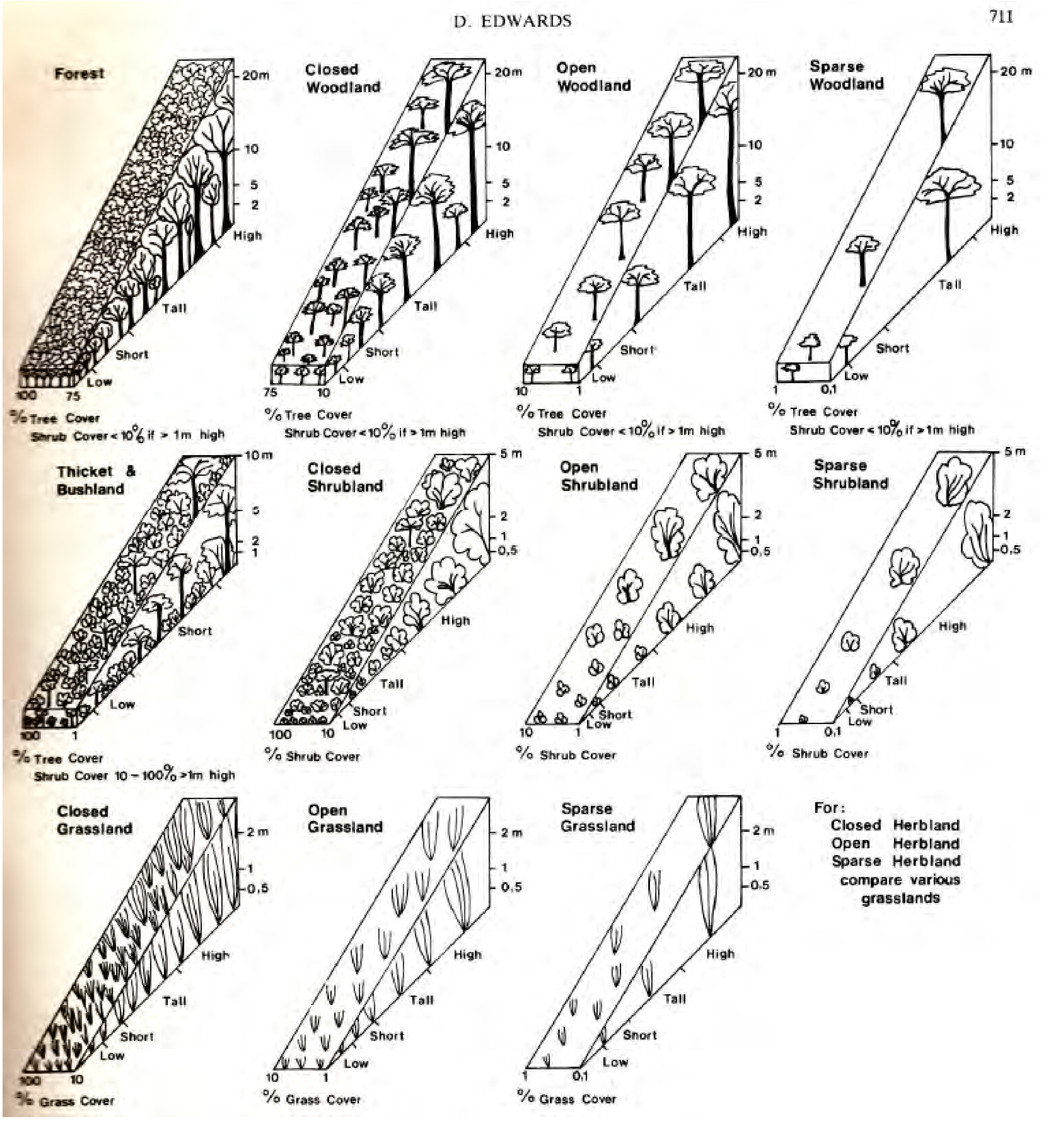
4. Reference

Henkel, J S, Ballenden S St.C, & Bayer A W, 1936. An Account of the Plant Ecology of the Dukuduku Forest Reserve and Adjoining areas of the Zululand Coast Belt. Annals of the Natal Museum, Vol. VIII, Part 1: 95-125.

Kotze D C, 2011. Burning of wetlands in timber plantation areas. Assessment criteria and guidelines. MWP Report No. 2011/1. Mondi Wetlands Programme, Irene.

Appendix 3: vegetation classification method

This section contains part of the (Edwards, 1983) paper on a broad scale vegetation classification method which was applied in this study. The grassland component was used to classify wetland vegetation structure.



The tables below are a summary of the image above.

Table 1: Height classes

	Trees	**Shrubs**	**Grasses and Herbs**
High	<20 m	2 – 5 m	>2m
Tall	10 – 20 m	1 – 2 m	1 – 2 m
Short	5 – 10 m	0.5 – 1 m	<0.5 - 1 mm
Low	2-5 m	<0.5 m	<0.5 m

Table 2: Primary cover classes

Cover	**Percentage Cover**	**Crown: Gap**
Closed	10 - 100	0 - 2
Open	1 – 10	2 – 8.5
Sparse	0.1 - 1	8.5 – 30
Scattered	<0.1	>30

Edwards, D. 1983: A broad-scale structural classification of vegetation for practical purposes. *Bothalia,* 14 (3/4): 705-712