Remote sensing applications for monitoring the spatial distribution of Bracken fern (*Pteridium*) in the Cathedral Peak: Drakensberg, South Africa.

Trylee Nyasha Matongera

215081306

A thesis submitted in the fulfilment for the degree of Master of Science in Environmental Sciences, in the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal.

Supervisor: Professor Onisimo Mutanga

Pietermaritzburg, South Africa

October 2016

Abstract

Bracken fern (*Pteridium*) is an invasive plant that presents serious environmental, ecological and economic problems world over. A comprehensive analysis of the current spatial distribution of bracken fern weeds is therefore essential for providing applicable management approaches at both local and regional scales. The main aim of the study was to assess remote sensing applications for monitoring the spatial distribution of bracken fern weeds in Drakensberg, South Africa. The first objective of the study focused on reviewing the progress and challenges in the remote sensing of bracken fern. Traditional mapping methods have been reported inefficient in discriminating the temporal and spatial distribution of bracken fern at a regional scale. The use of commercial satellite data with high resolution have demonstrated potential in providing fine spectral and spatial resolution capabilities that are essential to offer precise and reliable data on the spatial distribution of invasive species. Challenges encountered in remote sensing of bracken fern include problem of similarity in spectral signatures of bracken and other vegetation species leading to low classification accuracy. The second objective of the study assessed the effectiveness of the freely available Landsat 8 OLI sensor in detecting and mapping bracken fern. In evaluating the performance of Landsat 8 OLI in discriminating bracken fern, Landsat 8 OLI results were compared to that of Worldview-2. The study tested the utility of (i) spectral bands; (ii) derived vegetation indices as well as (iii) the combination of spectral bands and vegetation indices based on discriminant analysis classification algorithm. After resampling the training and testing data and reclassifying several times (n= 100) based on the combined data sets, the overall accuracies for both Landsat 8 and WorldView-2 were tested for significant differences based on Mann-Whitney U test. Findings of this study revealed that the combination of the spectral bands and vegetation indices yielded the best overall classification accuracy of 80.08% and 87.80% for Landsat 8 OLI and WorldView-2, respectively. There were significant differences {$U (100) = 569.5$, $z = -10.8242$, $p < 0.01$} between the classification accuracies derived based on Landsat OLI 8 and those derived using WorldView-2. Although there were significant differences between Landsat and WorldView-2 accuracies, the magnitude of variation (9%) between the two sensors was within an acceptable range. In this regard, considering the acquisition costs and limited spatial coverage for WorldView-2 sensor, it is recommendable to shift towards the use of freely and readily available new generation broadband sensors, such as Landsat 8 OLI.

Key words: Bracken fern, remote sensing, mapping, multispectral, encroachment, classification, spatial configuration, satellite imagery.

Preface

This study was conducted in the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa, from July 2015 to October 2016, under the supervision of Professor Onisimo Mutanga.

I declare that the work presented in this thesis has never been submitted in any form to any other institution. This work represents my original work except where due acknowledgements are made.

Trylee Matongera Signed …………………………. Date…………………….

As the candidate's supervisor, I certify the aforementioned statement and have approved this thesis for submission.

Professor Onisimo Mutanga Signed……………….. Date………………………..

Declaration

I Trylee Matongera, declare that:

1. The research reported in this thesis, except where otherwise indicated is my original research.

2. This thesis has not been submitted for any degree or examination at any other institution.

3. This thesis does not contain other person's data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted:

   a. Their words have been re-written and the general information attributed to them has been referenced.

   b. Where their exact words have been used, their writing has been placed in italics inside quotation marks and referenced

5. This thesis does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged, and the source being detailed in the thesis and in the references section.

Signed:……………………… Date………………………..

Dedication

I dedicate this dissertation to my beloved family, for believing so greatly in me and in the potential that I have to achieve greatness. I want to continue making you proud.

Acknowledgements

I would like to extend my gratitude to the University of KwaZulu-Natal, for giving me an opportunity to pursue my studies. Special thanks to the School of Agricultural, Earth and Environmental Sciences, this study would not have been possible without the opportunity that was given to me.

I would want to give my heart-felt appreciation to Professor Onisimo Mutanga my project supervisor who sacrificed a lot to make and enable me to come up with this wonderful piece of work. His professional expertise, enthusiasm and commitment towards supervising my work was excellent. I would also like to extend my gratitude to the entire University of KwaZulu-Natal community, with special thanks to Dr Timothy Dube, Mbulisi Sibanda and Dr Romano Lottering for their commitment towards mentoring me during my studies. Special thanks goes to my family for their unwavering support, you are a jewel and a pillar of strength in my life. I would also want to return my appreciation to my friends and colleagues, Auxcilia Kativhu, Eddy Mutsaa, Kudakwashe Marcia Chiwanza, Ashley Mashoko, Victor, Cletah Shoko, Sithabile Hlahla, Charles Otunga, Samuel Takudzwa, Shanell Sewel, Sam Nomuthandazo, Sizwe, Serge Kiala, Phindile and Nosipho for their encouragement during my study as well as for their unconditional financial and psychological support. I describe their devotion and love to be second to none. They are a gift from above and I thank God for them.

Table of Contents

List of Tables

List of Figures

Chapter One

General Introduction

1.1 Introduction

The increase in global landscapes invaded by invasive species has threatened future sustainability of agricultural, ecological and forest resources (Wulder and Franklin 2003). Bracken fern (*Pteridium*) in particular, is one of the major aggressive species encroaching into new productive landscapes, distressing agriculturalists and conservationists. Bracken fern has exceptional difficulties to farmers around the world. The fern spreads swiftly and outcompetes major agricultural crops such as maize and other cereal crops (Schneider and Fernando 2010). Due to the fern's persistent underground root system, once agricultural land is heavily invaded, farmers could possibly abandon the infected land. Recently, invasive species encroachment has been recognized as one of the foremost non climatic drivers of global change affecting economies in infected regions (Beck *et al.* 2008; Parry and Cox 2007). In the United States of America, the predictable budget of ecological damages related to management and control schemes of alien species such as bracken fern invasion is approximately US $137 billion per annum (Huang and Asner 2009). Ecologically, plant invasions have had substantial feedbacks with global climate processes (Field *et al.* 2007). Furthermore, the rate at which bracken fern spreads have direct relationship with ecological changes and processes such as increased nitrogen accumulation, atmospheric carbon dioxide concentration, preeminent air temperatures and unpredictable precipitation levels (Asner and Vitousek 2005; Dukes and Mooney 1999).

The speed at which bracken fern spread into new landscapes has been poorly presented and documented. Previous statistics on actual total area covered by the fern has been based on assumptions and limited data sets (Taylor 1990a). Continuous surveys in quantifying the extent of change in bracken spatial distribution have been restricted to small areas. Recentlty, remote sensing emerged as a reliable technique for ecological mapping and can therefore be used to design the best control and management approaches for invasive species. The developments in remote sensing of bracken fern could be traced back to the use of traditionally based mapping methods such as field surveys (Bunce *et al.* 1992), modelling (Pakeman *et al.* 1994) and aerial photographs (Tong *et al.* 2006). However, literature has shown that despite the advancement and efforts in traditional methods of mapping bracken fern, its spatial and temporal distribution cannot be determined using such methods. For example, Pakeman and Marrs (1996), combined data from both field surveys and modeling techniques to quantify landscapes that could be possibly invaded by bracken fern and also to identify major areas where global climate change would increase bracken fern prevalence. However, there were no results presented in terms of the speed at which bracken fern invades new landscapes, hence its distribution patterns remained unknown during that period.

Several studies have used medium spatial resolution satellite imagery in mapping the spatial and temporal distribution of bracken fern, examples of those studies include that of Miller *et al.* (1996) who investigated the bracken problem in Scotland using remote sensing. Taylor (1993), identified the potential of remotely sensed data for bracken encroachment monitoring in Australia as well as evaluating the impacts of management approaches. Recently, Odindi *et al.* (2014) successfully compared World View 2 and Spot 5 sensor images in characterizing bracken weeds using the random forest classifier. The use of medium spatial resolution images in the detection and mapping of bracken fern has been constrained by inadequate spatial and spectral capabilities (Pakeman *et al.* 1996; Singh *et al.* 2014). However, bracken fern research has generated much better results since the development of new high spatial resolution sensors that can detect bracken fern even at subspecies level (Ngubane, 2014).

High spatial resolution satellite imagery such as WorldView-2 offers a better potential in discriminating bracken fern even in areas with isolated bracken patches. Although these data sets have accurately mapped the spatial distribution of bracken fern, their application at a larger scale is limited considering their high acqusition costs. The rate at which the fern extents globally is still not clearly understood because of the scarcity of high spatial resolution sensors with a regional swath width. These limitations have of late resulted in a diversion towards the use of freely available broadband multispectral sensors with a global footprint and a repeated coverage, such as the Landsat datasets (Dube and Mutanga 2015). Moreover, Landsat datasets permit repeated regional scale mapping and monitoring. For instance, Dube et al (2015) concluded that the Landsat 8 sensor’s 16 day temporal resolution qualifies the sensor as one of the principal data sources appropriate and practical for large scale applications partculraly in areas with limited resources. Therefore, the current study aims at assessing remote sensing applications for mapping the spatial distribution of bracken fern in the Cathedral Peak: Drakensberg, South Africa.

1.2 Aims and objectives

The overall purpose of the study was to evaluate remote sensing applications for mapping the spatial distribution of bracken fern in the Cathedral Peak. The following objectives were set:

- To review the progress and challenges in the detection and mapping of bracken fern weeds using multispectral remotely sensed data
- To evaluate the effectiveness of the freely available medium resolution Landsat 8 OLI sensor in detecting and mapping bracken fern

1.3 Key research questions

- What are the major challenges and opportunities in remote sensing of bracken fern?
- Does the freely available Landsat 8 OLI sensor effectively detect and map bracken fern's spatial distribution?

1.4 Main hypothesis

- The freely available Landsat 8 OLI sensor with improved sensor characteristics has the potential to detect and map the spatial distribution of bracken fern with acceptable accuracies that are comparable to high spatial resolution WorldView-2.

1.5 General structure of the thesis

Excluding the introduction and the synthesis chapters (1 and 4) the thesis comprises of two research papers that answers each of the research questions in section 1.3. Consequently the literature review and methodology are entrenched within the mentioned papers.

Chapter two reviews the progress and challenges in the detection and mapping of bracken fern weeds, as well as tracking developments in bracken fern mapping over time using multispectral remotely sensed data. The study highlights remote sensing techniques in mapping bracken fern, including trade-offs between satellite mapping accuracy and image acquisition costs, as well as major challenges and strengths.

Chapter three focuses on assessing the utility of freely available Landsat 8 OLI sensor in detecting and mapping the spatial configuration of bracken fern. The study compared the results with those obtained using the high resolution WorldView-2 sensor. The choice of the high resolution WorldView-2 sensor was based on the sensor's proven track record in bracken fern detection and mapping with high accuracy. The comparison was conducted to assess the magnitude of difference in accuracies between the two sensors.

Chapter Two

A review of the detection and mapping of bracken fern weeds using multispectral remotely sensed data

This chapter is based on a published review paper:

Matongera, T. N., Mutanga, O., Dube, T. & Lottering, R. T. 2016. Detection and mapping of bracken fern weeds using multispectral remotely sensed data: A review of progress and challenges. *Geocarto International*, 1-31. TGEI-2016-0117.R1.

Abstract

Bracken fern is one of the major invasive plants distributed all over the world currently threatening socio-economic and ecological systems due to its ability to swiftly colonize landscapes. The study aimed at reviewing the progress and challenges in detecting and mapping bracken fern weeds using multispectral remotely sensed data. Evidence from literature have revealed that traditional methods such as field surveys and modelling have been insufficient in detecting and mapping the spatial distribution of bracken fern at a regional scale. The applications of medium spatial resolution sensors have been constrained by their limited spatial, spectral and radiometric capabilities in detecting and mapping bracken fern. On the other hand, the availability of most of these data sets free of charge, large swath width and their high temporal resolution have significantly improved remote sensing of bracken fern. The use of commercial satellite data with high resolution have also demonstrated potential in providing fine spectral and spatial resolution capabilities that are essential in offering precise and reliable data on the spatial distribution of invasive species. However, the application of these data sets is largely restricted to smaller areas due to high acquisition costs. Studies on bracken fern classification have extensively adopted traditional classification methods such as supervised maximum likelihood classifier. Finally, since high spatial resolution sensors are expensive to acquire and have small swath width, the current study recommends that future research can also consider investigating the utility of the freely available recently launched new generation sensors such as Landsat 8 OLI with a global footprint which provides invaluable information for repeated measurement for bracken fern weeds over time and space.

Keywords: Bracken fern, mapping, encroachment, global distribution, spatial configuration, classification, satellite imagery.

2.1 Introduction

Invasive species proliferation is a substantial global change phenomenon that progressively influences biodiversity, ecosystem function, agricultural productivity and human livelihood (Burgiel and Muir 2010; Schneider and Geoghegan 2006). Bracken fern (*Pteridium*) is ranked amongst the greatest invasive species world over (Holland and Aplin 2013). The fern's intrusion has caused great reduction in the quantity and quality of land accessible for grazing (Birnie and Miller 1986). Literature has shown that the fern obstructs secondary forest re-establishment, and does not deliver adequate quality biomass, which improves soil nutrients regeneration (Oldham *et al.* 2013; Schneider and Geoghegan 2006). Empirical evidence from literature have shown that spatial data on bracken fern's spread, its life cycle and fern status cannot be accurately mapped using field surveys in the remote and inaccessible mountainous environments world-wide (Odindi *et al.* 2014, Ngubane 2014; Mehner *et al.* 2004). Several studies have used available remote sensing platforms for detection and mapping bracken fern spatial distribution at various scales (Singh *et al.* 2014; Ngubane 2014; Holland and Aplin 2013; Miller *et al.* 1990). Some examples of those studies also include that of Miller *et al.* (1996) who investigated the bracken problem in Scotland using remote sensing. Taylor (1993), identified the potential of remotely sensed data applications for bracken encroachment monitoring in Australia as well as evaluating the impacts of management approaches. Recently Odindi *et al.* (2014) successfully compared WorldView-2 and Spot 5 imagery in characterizing bracken weeds using the robust random forest classification algorithm.

Earlier reviews on bracken fern include those by Chavasse and Davenhill (1973) who discussed chemical control of bracken fern for forest development. The review by Taylor (1990a) addressed the bracken problem at a global perspective. McGlone *et al.* (2005), presented a comprehensive review on ecological and historical review of bracken in New Zealand, and its cultural significance. Vetter (2009), reviewed bracken fern as the biological hazard of our age, focusing on its ecological distribution and carcinogenic properties. The works of Mehltreter *et al.* (2010) successfully assessed the bracken fern ecological aspects, uncovering problems associated with ferns and their impact management. However, the above mentioned reviews have been centered on the general ecophysiological properties of bracken fern, as well as its impacts on humans and foraging animals. To the best of the researcher's knowledge, there is no review that has focused on various remote sensing applications that have been used in detecting and mapping of bracken fern weeds. In this regard, it is clear that there is need for a comprehensive review on the progress and challenges in remote sensing of bracken fern in order to identify the most important remote sensing techniques that can help to improve remote sensing of invasive species such as bracken fern.

The current study reviews the progress and challenges as well as the available techniques in detection and mapping of bracken fern weeds at various scales. Firstly, the study provides a brief overview of the ecology and spatial distribution of bracken fern globally, providing a summary on various regions of the world affected by bracken fern. Secondly, the study highlights remote sensing techniques in mapping bracken fern, including trade-offs between satellite mapping accuracy and image acquisition costs, as well as challenges and strengths. The adequate spatial, spectral and temporal resolutions optimal for bracken fern mapping are debated. Also, included in this review is a discussion on the techniques to classify bracken using remotely sensed data, focusing on field data collection methods, image pre-processing, classification algorithms and validation procedures. A detailed summary on the different methods available, as well as future endeavors in mapping and monitoring bracken fern invasive species is also highlighted.

2.2 The ecology and spatial distribution of bracken fern

Bracken fern (*Pteridium*) are different invasive species, which include *Aquilinum, Esulentum, and Arachnoideum* amongst others (Der *et al.* 2009). Bracken plant is a huge fern which grows rapidly, the fern has fronds that are composed of smaller leaflets, shaped like triangles. The subtropical fern develops abundantly in summer seasons, unveiling live and healthy green fronds, and it withers and die in winter and produces dense mass of red or brown matter (Holland and Aplin 2013). Figure 2.1 shows stages in the phenological cycle of subtropical bracken fern in different seasons. Bracken has the ability to grow at a rate of as much as 2.1m in one season (Fletcher and Kirkwood 1979). Parks and Werth (1993), postulated that rapid growth of bracken may result in extensive spread into other useful habitats. Main botanical aspects of bracken fern include extreme high rate of production, quick re-growth and rapid adaptation to various ecological conditions (Vetter 2009). In an attempt to combat the impact of bracken encroachment on agricultural land, farmers resorted to spraying bracken with chemicals, such as Asulam (Pakeman and Marrs 1992). The use of chemicals to control bracken weeds has been considered as a short term measure, because the fern has rapid regrowth (Engelman and Nyland 2006). There is also debate about whether or not these chemicals affect surrounding vegetation or toxic to stock (Pakeman *et al.* 1996). Roos *et al.* (2010), studying tropical bracken noted that burning bracken fern as a method of controlling its spread discharges dominance of fully mature bracken fronds, just like as cutting does, this consequently promoting bud break. The mechanical treatment assist in the reduction of carbohydrates reserves in bracken rhizome because of the deletion of photosynthetic ferns Lowday and Marrs (1992), thus suppressing bracken multiplication.

Photograph	Season and description
	**Spring**: Spore maturation and dispersal begins at the base of the frond and proceeds up to the tip resulting in an extended period of spore dispersal (Cody and Crompton 1975).The fern starts to develop microorganisms. Brand new growth has a single unbranded stem, with considerably short unbranched leaves originating from the stem (Wild-Flowers 2014). The top part is kinky, with a fiddle head, and increasingly unrolls as it grows.
	**Summer**: live bracken with healthy leaves and inflexible grooved stem. Leaflets shiny on upper surface with bright green terminators (Wild-Flowers 2014). Bracken leaflets are opposite each other. There is a faint herringbone- pattern of raised bumps. Bracken grows quickly in summer exhibiting vigorous vegetation.
	**Winter**: Due to frost bracken fronds withers and falls on the ground. It eventually dies back and form a dense brown matter (Holland and Aplin 2013). During winter season the crushed dead bracken insulates spores from the cold that may be germinating. The fronds killed by frost are regenerate in mid-July (Conway 1957).

Figure 2.1: Detailed description of temperate/ subtropical bracken fern phenological cycle, photographs by Holland and Aplin (2013).

There has been a debate on the ecological importance of bracken fern. Although ferns are an integral part of the world's flora, appreciated for their beauty as ornaments, they are problematic as invaders (Mehltreter *et al.* 2010). Bracken fern is now regarded as a problem plant (Taylor 1986), because of its ability to colonize and outcompete other plant species for nutrients, moisture and other environmental requirements essential for plant growth. On the other hand Pakeman *et al.* (1996) argued that bracken has an important ecological value such as providing habitation for small animals such as nightjar and skylark. In some cases the fern can also be used as a refuge by bluebell plant and grouse from potential predators. According to Aplin (2004) traditionally, bracken was gathered for a wide variety of uses which include manure, thatch and animal bedding. Pakeman *et al.* (1996), established that the deterioration in these uses has revealed that it is no longer regarded as a useful resource that requires to be conserved. Despite these conflicting debates, there is an ecological necessity to understand the distribution, rapidity and magnitude with which bracken fern colonies new landscape. In this regard, there is a clear necessity for effective mapping of the spatial and temporal distribution of bracken.

Bracken fern is a weed of worldwide distribution (Taylor 1986), available in a diversity of climates, altitude and latitudes excluding the cold and hot desert areas (Page 1976). The exact origin of bracken fern can be difficult to trace. However, many sites in the United Kingdom have many bracken archeological remains dating from the Neolithic and Bronze ages through to the industrial revolution (Fuller *et al.* 1994). Bracken is widely distributed typically in the Northern hemisphere. It is also reported to be a successful fern in many countries, such as Australia (Fletcher *et al.* 2010; Taylor 1990b), Mexico (Schmook *et al.* 2011b; Schneider and Fernando 2010), Ecuador (Curatola Fernández *et al.* 2015; Göttlicher *et al.* 2009), Scotland (Miller *et al.* 1990; Birnie and Miller 1986), New Zealand (McGlone *et al.* 2005), Germany (Taylor 1986), France (Gamblin *et al.* 1986) and South Africa (Ngubane 2014; Odindi *et al.* 2014). Previous studies indicated that bracken genets are smaller and numerous in the Northeastern United States population when compared to Great Britain populations as evidenced by the bracken global distribution map in Figure 2.2 (Sheffield *et al.* 1989, Wolf *et al.* 1987). However, the best possible explanation for the differences between northeastern bracken populations could be differing ecological and historical circumstances encountered by those populations.

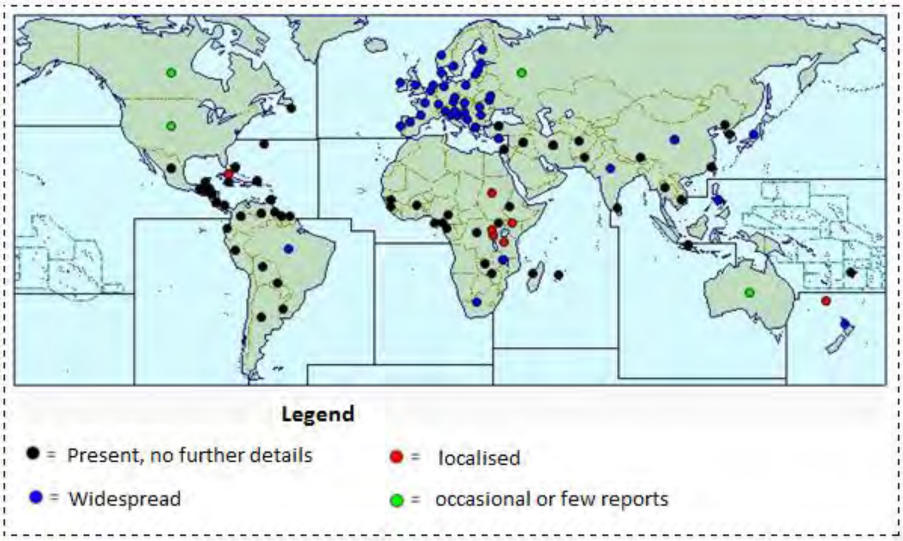

Figure 2.2: Global distribution map for bracken fern; adapted from Invasive_Species_Compendium (2005)

2.3 Remotely sensed spectral characteristics of bracken fern

Vegetation species have comparable general properties that determines their spectral reflectance. These comprise of water content, arrowroots, light absorbing pigments, chlorophyll and structural biochemical compounds (Adam *et al.* 2010; Kokaly *et al.* 2003; Price 1992). Bracken reflectance is influenced by its physiological structure and spatial alignments. Generally, bracken fern field reflectance measurements are statistically different from those of other vegetation (Taylor 1993). In most cases landscapes containing the fern variegated with other plant species have considerable different spectral reflectance compared to areas where bracken fern dominates (Roy Chowdhury and Schneider 2004). Bracken fern is discreet in specific spectral wavebands in different seasons of the year. Specifically in the visible wavebands, the weed is much similar to other vegetation species such as grasses in summer season when vegetation is abundantly green (Holland and Aplin 2013). During winter the fern has higher reflectance values when compared to other vegetation species, especially the red part of the spectrum because of its richness in dead material as illustrated in Figure 2.3. Previous study by Singh *et al.* (2014) revealed that bracken spectral reflectance value in the NIR band is unique and distinguishable from non-bracken fern class. While the spectral reflectance pattern of bracken fern and other vegetation class look similar in the RGB bands of mid-spring imagery. Budreski *et al.* (2007) and Lillesand *et al.* (2008) summarised that during mid-spring bracken fern has the peak reflectance of all the land cover features in the NIR band due to the existence of chlorophyll.

Bracken limited classification precision is normally accredited to its ecophysiological properties and spatial conformations (Pakeman *et al.* 1996). Experimental studies have highlighted that bracken properties such as percentage canopy cover and biomass influence spectral reflectance (Blackburn and Pitman 2010; Taylor 1993; Birnie 1985). Like other plants, bracken pigments (i.e. carotenoids) have an effect on reflectance properties, particularly the green segment of the electromagnetic spectrum. However, bracken reflectance properties in the near infrared are determined by differences in frond structures (Gates *et al.* 1965). Bracken canopy which is collection of assortment of fronds, stems as well as chemical composition also influences the fern’s spectral reflectance (Wessman *et al.* 1997).

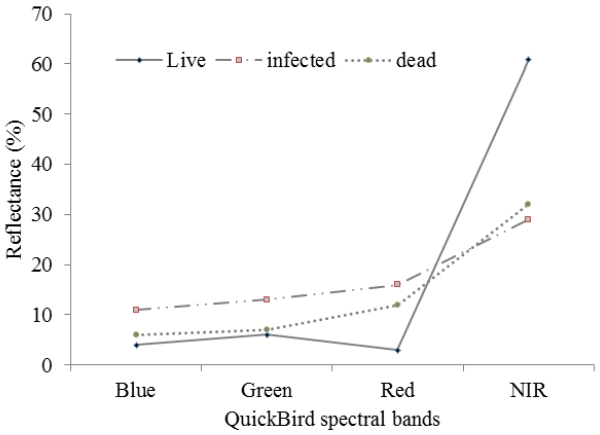

Figure 2.3: Average field-derived reflectance of live, dead, and infected bracken fronds spectrally resampled to four Quickbird bands i.e. blue, 450nm; green, 520-600nm; red, 630-690nm and NIR, (760-900nm Curatola Fernández *et al.* 2013).

Bracken fern morphology has a direct impact on its reflectance. These factors include optical, structural and biochemical properties of bracken. Similar to other vegetation species such as grasses, bracken fern has numerous particles and pigments forming a portion of compound arrangement of vegetation cells that absorb and distribute radiation at different wavelengths. (Van Der Meer and de Jong 2001). Various scholars have addressed the clonal structure of populations in bracken. Oinonen (1967), uncovered the size of bracken genets based on morphological features and tracing of rhizomes resulted in underestimates of clonal size. Bracken frond epidermal cells center radiation; on the other hand palisade cells serve as radiation tubes whilst mesophyll cubicles scatter radiation. (Myers *et al.* 1994; Vogelmann and Martin 1993). The visible region of the electromagnetic spectrum represents maximum variation where bracken chlorophyll absorbs dimly and minimal variation emerges in the violet blue spectrum part where pigments absorb strongly. Variability in the NIR is normally high for reflectance and transmittance but low for absorption (Knapp and Carter 1998).

2.4 Remote sensing of bracken fern

The developments in detection and mapping of bracken fern can be retraced back to the usage of traditionally based mapping methods, such as field surveys (Bunce *et al.* 1992), modelling (Pakeman *et al.* 1994) and aerial photographs (Tong *et al.* 2006). Literature have shown that field surveys comprise of field data collection surveys using global positioning system (GPS) and environmental parameters such as topography, climate and soils (Pakeman *et al.* 1996). In most research studies, although the focus of the studies will be on bracken fern, other dominant land cover classes are recorded during field data collection. Mathematical models have been used to quantify the spatial distribution of bracken fern as well as predicting the risk of future invasions (Pakeman *et al.* 1994). Most traditional mapping methods have not been successful in detecting and mapping the spatial configuration of bracken fern, especially at a regional scale. Bunce *et al.* (1992), used sample based field surveys of 508 1-km^2 on Britain's land cover map to account for the distribution of bracken fern. The spread of bracken into new areas was poorly presented because the study was based on assumptions and limited field data. Pakeman *et al.* (1994), accounted for the distribution of bracken using mathematical models. The study presented a mechanist physiological model for the growth of bracken which describes yearly cycle in terms of rhizome carbohydrate, rhizome tissue and frond biomass. However there were no results presented in terms of the speed at which bracken fern invades new landscapes, hence its distribution patterns remained unknown during that period. Pakeman and Marrs (1996), combined data from both field surveys and modeling techniques to recognize landscapes that could be possibly invaded by bracken fern and also to identify major areas where global climate change would increase bracken fern prevalence. From the evidence drawn from literature, it is clear that despite the advancement and efforts in traditional methods of mapping bracken fern, its spatial and temporal distribution cannot be determined using such methods.

Through the use of satellite imagery, remote sensing has proved to be a reliable source of environmental data and has become common in ecological research supplying precise and reasonable method of obtaining data over large areas (Aplin 2005). Remote sensing technology has been confirmed to be crucial in mapping vegetation distribution because of its high temporal and spatial data quality (DeFries *et al.* 2004). Generally, remote sensing of bracken fern has already been a subject of research in many countries including Ecuador (Curatola Fernández *et al.* 2015; Curatola Fernández *et al.* 2013; Göttlicher *et al.* 2009), Australia (Taylor 1990b;Taylor 1986), Scotland (Miller *et al.* 1990; Birnie and Miller 1986) , United Kingdom

(Mehner *et al.* 2004; Holland and Aplin 2013; Pakeman *et al.* 1996), Mexico (Schmook *et al.* 2011a;Schneider and Fernando 2010; Suazo 1998) and South Africa (Odindi *et al.* 2014; Ngubane 2014; Singh *et al.* 2014). Table 2.1 presents a summary of some of the most important remote sensing studies on detection and mapping of bracken fern in different parts of the world. In addition, a detailed information on remote sensing applications, types of sensors used, and image processing techniques employed and major research findings in those studies is presented. The most common sensors that have been used in remote sensing of bracken fern to date include the Landsat series (Curatola Fernández *et al.* 2015; Holland and Aplin 2013; Schneider and Fernando 2010; Pakeman *et al.* 1996) , Quick Bird (Curatola Fernández *et al.* 2013), IKONOS (Mehner *et al.* 2004), SPOT-5 (Odindi *et al.* 2014). WorldView-2 (Ngubane 2014; Odindi *et al.* 2014). Medium resolution satellite imagery like Landsat 5 MSS satellite imagery was proven less accurate in bracken mapping (Birnie and Miller 1986). In this case Landsat MSS 60m coarse spatial resolution as well as its restricted spectral abilities containing only four traditional bands were a limiting factor. Holland and Aplin (2013), compared Landsat ETM+ and IKONOS in mapping bracken fern. The study summarized that Landsat ETM+ imagery was more efficient than IKONOS in mapping the distribution of bracken fern as presented in Table 2.1.

The launching of new innovative satellite imagery with more finer spatial resolution and additional purposefully located spectral bands offer unrestricted prospects for bracken mapping. Fine spatial resolution satellite imagery such as WorldView-2 which obtains 11 bit multispectral data in eight spectral bands has been successful in bracken fern mapping (Ngubane 2014; Odindi *et al.* 2014). Due to availability of narrow spectral channels, new generation sensors have demonstrated great potential in mapping and discriminating bracken fern. Using high spatial resolution Ikonos sensor, Mehner *et al.* (2004), concluded that the research findings of image processing underscored that remote sensing technology is much useful in bracken fern mapping compared to traditional ground based survey techniques. Furthermore, the assessment technique revealed that Ikonos image classification results scored remote sensing accuracies of around 80%. The relationship between satellite data acquisition costs, availability and mapping accuracy has been a major factor influencing invasive vegetation mapping (Xie *et al.* 2008). Notwithstanding the reported prosperous application of high spatial and spectral resolution sensors in detection and mapping of bracken fern, as presented in Table 2.2, it can be noted that high spatial resolution sensors are associated with high acquisition costs and limited swath width, etc. (Dube *et al.* 2016). These data sets are priced per square kilometer, as the area of coverage increases, the cost increases too. However, the optimal sensor characteristics which are adequate for detection and mapping bracken fern remain a challenge.

The debate on the adequate spatial, spectral, radiometric and temporal resolutions in detection and mapping of bracken fern is a complex discussion that cannot provide a clear cut or benchmark of sensor characteristics that can be optimal used in mapping bracken fern. Instead a critical appreciation of different types of sensors, sightseeing their spatial, spectral, radiometric and temporal capabilities and limitations in bracken fern mapping is necessary. Both medium and high spatial and spectral resolution sensors have been utilized in remote sensing of bracken fern. However, like other invasive species, bracken fern is normally concealed in a background of other vegetation species such as grassland (Huang and Asner 2009), making it challenging to detect using medium spatial resolution. On the other hand, high spatial resolution sensors offers a better potential in discriminating bracken fern even in areas charecterised by isolated bracken patches. Basing on the research findings from literature it is not reasonable to conclude that neither medium nor high spatial and spectral resolution sensors has adequate sensor characteristics required for optimal detection and mapping of bracken fern weeds. Medium resolution sensors such as 30m Landsat have limited spatial characteristics which restrains the detection of bracken fern, while their 16 day temporal resolution and larger swath width (185km) offers a great potential in remote sensing of bracken fern. High spatial resolution satellite imagery such as WorldView-2, Ikonos and Quickbird with less than 5m spatial resolution can accurately detect the fern, whereas their high acquisition costs, low temporal resolution and smaller swath width remains a huge challenge in detecting spatial configuration of bracken fern at a regional scale. In this regard, since there is no clear benchmark set yet for adequate sensor characteristics in bracken fern mapping it is recommendable that both medium and high spatial and spectral resolution sensors can be utilized with regards to magnitude of mapping accuracy expected in that specific study and the size of bracken fern's patches. To improve bracken fern mapping, it is advisable to focus on improving the spatial and spectral characteristic of freely available sensors such as Landsat series which already has high temporal resolution and large swath width which provides a global foot print in mapping the fern. Improvements on freely available sensors with global coverage will assist in multi-temporal mapping of bracken fern weeds using remotely sensed data.

Several researchers adopted an investigational approach to multi-temporal remote sensing of bracken fern. For instance research findings by Holland and Aplin (2013) revealed that winter satellite imagery has proved to be accurate for single date classification of bracken fern. On the other hand, the use of multi-temporal imagery accurately provided a detailed description of the seasonal vegetation variation. Using multi-temporal Landsat satellite data Curatola Fernández *et al.* (2015) provided a rock-solid platform for land cover alteration investigation in the tropical Andes of south-eastern Ecuador. Their research study reported meaningful research findings in the collection of five Landsat scenes from the year 1975 to 2001. The study was an important achievement towards classification of land-cover change since it was an elongated period of remotely sensed based land cover change research that included analysis of bracken fern in the Andes of Ecuador. Multi-temporal remote sensing enables ecologists and researchers to quantify the rate at which bracken fern spreads and possible factors influencing the encroachment. For example Curatola Fernández *et al.* (2015) established that the use of fire as a method of land clearance encouraged the infestation of land by bracken fern, since spatial encroachment of bracken fern doubled between 1987 and 2001. Similarly Schneider and Fernando (2010) estimated the variations in spatial distribution and seasonal variations of bracken weeds encroachment in Southern Yucatan from 1989 to 2005. The research findings reported an escalation total area covered by bracken fern from 40km^2 in 1989 to almost 80km^2 in 2000. Moreover, multi-temporal remote sensing of bracken fern enabled the understanding of the spatial extent and annual unevenness of bracken fern cover in the region, as well as determining the relationship between disturbances, such as fire and forest recovery. Despite the conclusions drawn from literature on the successful application of multi-temporal remote sensing of bracken fern, it is still necessary to develop and supplement research studies on ecological processes interconnected to remotely sensed data, which improve the understanding of plant invasions and their relation to anthropogenic and natural disturbances.

Table 2.1: Summary of remote sensing applications in bracken fern mapping

Study/Applications	**Sensor (s) used**	**Image analysis technique (s)**	**Results**	**Reference**
Land cover change in the Andes of Southern Ecuador-Patterns and Drivers.	Landsat Multispectral Scanner (MSS) Landsat TM Landsat ETM+	Maximum likelihood classification	94.5% to 98.5% OA Kappa between 0.75 and 0.98	(Curatola Fernández *et al.* 2015)
The evaluation of high resolution aerial imagery for monitoring of bracken fern.	Aerial Imagery	Maximum likelihood classification	Winter OA for bracken - 81.43%, Kappa 0.63 Spring OA for bracken - 94.44%, Kappa 0.89	Singh *et al.* (2014)
Assessment of the contribution of WorldView-2 strategically positioned bands in bracken fern (*Pteridium aquilinum*) mapping	WorldView-2 SPOT 5	Maximum likelihood classification	WorldView-2 bands OA- 73.77% WorldView-2 traditional bands OA- 70.27% WorldView-2 additional bands OA- 99.14% SPOT 5 OA- 66.15%	(Ngubane 2014)
Comparison between World View-2 and Spot 5 Images in mapping bracken using random forest algorithm	World View-2 Spot 5	Random Forest Algorithm	WorldView-2 OA- 91.67% Spot 5 OA- 72.22%	Odindi *et al.* (2014)
Bracken fern frond status classification in Andes of Southern Ecuador: Combining multi-spectral satellite data and field spectroscopy	Quickbird	Maximum likelihood classification	OA- 0.9973, Kappa 0.9927 Bracken fern UA- 0.9979, PA- 0.9771	Curatola Fernández *et al.* (2013)
Super resolution image analysis as a means of monitoring bracken (*Pteridium Aquilinum*) distributions.	Landsat TM Landsat ETM+ IKONOS	Maximum likelihood classification Super resolution analysis	Landsat TM OA- 70% Landsat ETM+ OA- 90% IKONOS OA- 78.4%	Holland and Aplin (2013)

A step-wise land-cover classification of the tropical forests of the Southern Yucatán, Mexico	Landsat ETM+	In-Process classification Assessment (IPCA)	Bracken fern class: Kc 0.72, UA 73%, PA 90%	(Schmook *et al.* 2011a)
An untidy cover: Invasion of bracken fern in the shifting cultivation systems of Southern Yucatan, Mexico.	Landsat ETM	Linear Mixture Model (LMM)	1989 KIA for bracken- 0.4079 2000 KIA for bracken- 05254	Schneider and Fernando (2010)
Land-cover classification in the Andes of southern Ecuador using Landsat ETM+ data as a basis for SVAT modelling.	Landsat TM	Maximum likelihood classification	87.3% OA 95% confidence interval 0.86 Kappa value	(Göttlicher *et al.* 2009)
Monitoring of the Ecuadorian mountain rainforest with remote sensing	Landsat MSS Landsat TM Landsat ETM+	Minimum distance classification Maximum likelihood classification	Minimum distance OA- 62.6% Maximum likelihood OA- 68.9%	(Goerner *et al.* 2007)
Remote sensing of upland vegetation: The potential of high spatial resolution satellite sensors.	IKONOS	Unsupervised ISODATA classification	Summer image OA- 74.3% Winter image OA- 53.4 %	Mehner *et al.* (2004)
Bracken problem in Britain, analyzing present and future changes.	Landsat TM	Maximum likelihood classification	85% classification accuracy	Pakeman *et al.* (1996)

Table 2.2: Remote sensing sensor specifications and cost in bracken fern mapping

Sensor	**Spectral bands**	**Spatial resolution (m)**	**description**	**Swath-width (km)**	**Revisit time (days)**	**Cost of image acquisition (US $/km^2)**
Landsat Thematic Mapper (TM)	7	30 120	Band (1-5 and 7) Band 6	185	26	Free
Landsat Enhanced Thematic Mapper plus (ETM+)	8	30 15	Band (1-7) Band 8	185	18	Free
Moderate resolution Imaging Spectrometer (MODIS)	36	250 500 1000	Band (1-2) Band (3-7) Band (8-36)	2330	1-2	Free
Sentinel 2	13	10 0 60	Band (2, 3, 4 and 8) Band (5, 6, 7, 8a, 11, and 12) Band (1, 9 and 10)	290	5	Free
RapidEye	5	5	All bands	77	1 (off nadir) / 5.5 (nadir)	US $1.28
Système Pour l'Observation de la Terre 5 (SPOT 5) High-Resolution Stereoscopic (HRS) High Resolution Geometric (HRG) Vegetation (VGT)	5	10 20	Band (1-3) Band 4	60	2.5	US $5.15
Quickbird	5	2.40 0.60	All multispectral bands Panchromatic band	16.8	1-3.5	US $24
World View-2	8	2 0.46	All multispectral bands Panchromatic band	16.4	1.1	US $28.5
World View-3	8	1.24 0.31	All multispectral bands Panchromatic	13.1	1	US $29

2.5 Bracken fern classification techniques

Bracken fern classification has been employed using both traditional (Curatola Fernández *et al.* 2013; Mehner *et al.* 2004; Pakeman *et al.* 1996) and advanced robust (Odindi *et al.* 2014; Holland and Aplin 2013) image classification techniques. Classification algorithms that have been used in bracken fern studies include maximum likelihood, unsupervised ISODATA, Linear Mixture Model (LMM), super resolution analysis and random forest algorithm. Research findings from this review have showed that most research studies on remote sensing of bracken fern as presented in Table 2.1 have used traditional maximum likelihood classification approach (Ngubane 2014; Singh *et al.* 2014; Curatola Fernández *et al.* 2013; Holland and Aplin 2013; Göttlicher *et al.* 2009; Pakeman *et al.* 1996). Maximum likelihood classifier is usually regarded as a classic and most widely used supervised classification for satellite images resting on the statistical distribution pattern (Xie *et al.* 2008; Xu *et al.* 2005; Sohn and Rebello 2002). The overall accuracy results obtained in most studies using maximum likelihood in bracken classification ranges between 68% and 85%. Although good results have been obtained using traditional classifiers such as maximum likelihood, classification of bracken fern using maximum likelihood becomes difficult in cases where bracken is mixed with secondary vegetation (Schneider and Fernando 2010). However, the combination of soft classifiers such as fuzzy classification and maximum likelihood have shown an improvement in bracken fern classification (Singh *et al.* 2014).

For improved bracken fern discrimination from existing land cover classes, robust and cutting-edge algorithms are now being used for classification. These include random forest algorithm and super resolution analysis. The overall accuracy results obtained in most studies that have used advanced robust classifiers in bracken classification ranges between 71%-98%. However, bracken fern mapping can also adopt emerging machine learning and statistical classification algorithms that have been successfully applied in vegetation mapping. These include Artificial neural network (Linderman *et al.* 2004; Hilbert and Ostendorf 2001; Civco 1993), Support vector machines (Su *et al.* 2007; Huang *et al.* 2002; Huang *et al.* 2002) and Discriminant analysis (Sibanda *et al.* 2015; Fraley and Raftery 2002). For better classification accuracy of remote sensing imagery, there is need to perform pre-processing procedures. Some of the most important image pre-processing techniques which have been performed in detection and mapping of bracken fern studies include atmospheric correction (Schmook *et al.* 2011b), topographic correction (Curatola Fernández *et al.* 2015; Göttlicher *et al.* 2009), geometric correction (Mehner *et al.* 2004), orthorectification (Singh *et al.* 2014; Göttlicher *et al.* 2009), radiometric intercalibration (Curatola Fernández *et al.* 2015), image enhancing and masking for clouds (Curatola Fernández *et al.* 2015) and on top-of-atmosphere reflectance conversion (Odindi *et al.* 2014). However, the above mentioned preprocessing procedures may not always be needed in every image because some of these preprocessing procedures may have been already performed by the image distribution agencies. Therefore it is necessary to consult with the image suppliers in order ~~to get~~ to know at which level the image was distributed.

All the aforementioned classification algorithms in bracken fern detection and mapping require accuracy assessment. For the validity and reliability of the results, accuracy assessment is performed for each class. Confusion matrices generated by the classification model are used to calculate accuracy assessment. Agreement between classification results and ground truth data is usually measured using the producer accuracy (PA), user accuracy (UA) and overall accuracy (OA) generated from the confusion matrices (Mushore *et al.* 2016; Jia *et al.* 2014). Validation of accuracy assessment in remote sensing is an important aspect which is used to determine the precision of the classification (Congalton 2001). Bracken fern studies have used a validation method whereby reference data is split into two categories, with 70% of the samples for training and 30% for testing (Odindi *et al.* 2014; Ngubane 2014). Literature has also reported the use of kappa coefficient in validation of accuracy in bracken fern classification (Curatola Fernández *et al.* 2015; Schmook *et al.* 2011a; Mehner *et al.* 2004). The kappa coefficient has been interpreted as a value of the difference between observed agreement of the classification and reference data, showing the precision of the classification (Campbell and Wynne 2011). In this regard, basing on the reviewed literature it has been discovered that although other advanced classification algorithms yields better results than traditional methods, no single classification algorithm can be considered as an optimal methodology for the detection and mapping of bracken fern. Henceforth, the choice of classification algorithms must be based on their suitability to achieve certain objectives in specific studies.

2.6 Challenges in remote sensing of bracken fern invasive species

Bracken fern develops on a comprehensive variety of spatial structures originating from isolated fronds, thick patches and completely covered hillsides (Marrs and Hicks 1986). This makes it difficult for medium resolution imagery to accurately capture bracken reflectance (Harvey and Hill 2001). Bracken fern exhibits high spectral and spatial variability (Blackburn and Pitman 2010), as a result it is challenging to identify clear boundaries between bracken fern and other vegetation types. Although there has been constant advancement in spatial resolution and strategically positioned spectral bands, mixed pixels challenge still hinders clear identification of bracken fern boundaries. (Laba *et al.* 2008; Fuller *et al.* 1994). Recently Singh *et al.* (2014) established that spectral reflectance patterns of bracken and non-bracken class was similar in the RGB bands of the mid-spring imagery, hence leading to spectral confusion. In this regard the classified image depicted high error of commission for bracken fern class. The results indicated that the classifier is likely to have confused bracken fern with other vegetation types. Mehner *et al.* (2004), encountered the same challenge during bracken fern classification using IKONOS imagery. In their study, during classification higher class number was incorporated; hence mixed pixels resulted in misclassification of vegetation spectral characteristics. Research work by Foody *et al.* (2005) and M.-Muslim *et al.* (2007) failed to clearly interpolate boundaries between the fern and other vegetation classes. Despite the fact that most classifiers provided room for pixel positioning and spacing it is not clear enough to discriminate bracken fern at species level (Drake 2000).

Topographic shading has ~~been~~ a challenge in vegetation mapping discipline. Retrieval of bracken fern reflectance is problematic particularly in case of topographic shading. Terrain shadows influence bracken reflectance patterns. High computing power and complex high spatial resolution digital elevation models (DEMs) maybe required for topographic correction so as to reduce the effects of terrain shadows (Asner and Vitousek 2005). Moreover, considering that bracken fern is commonly found in moorlands and high mountainous areas, low resolution satellite imagery may not provide clear images for bracken sampling plots with rugged terrain. ~~Research study by~~ Mehner *et al.* (2004), established that winter image had a shadow for areas with steep relief, this prejudiced classification from the IKONOS imagery. The classification of bracken fern in the mountainous areas such as the Andes of the Ecuador clearly presents some of the challenges of remote sensing of bracken fern species in relation to topography. For example the works of Curatola Fernández *et al.* (2015), in the Andes of southeastern Ecuador concluded that although good results were obtained, remote sensing applications in this area were challenging because the complex topography distorted the satellite signal and the high cloud frequency complicated the acquisition of images. Due to the southeastern Ecuador mountainous landscape, the study by Göttlicher *et al.* (2009) concluded that there was need for proper land-surface classification in high mountain areas using complex topographic normalization of radiances. This was based on the complex DEM which proved the slope and aspect of every pixel and the calculated sun elevation and azimuth angles. Similarly, Schneider and Fernando (2010) also concluded that characterizing tropical land covers at a regional level proves challenging as land covers in tropical areas ~~are~~ untidy and land transformations are dynamic.

The use of aerial photography is one of the ~~generally~~ commonly used methods which limit data collection. Usually aerial photography collects a lesser swath width of data from aircraft and this can limit the capability for large scale mapping. Using LIDAR Singh *et al.* (2014) encountered rigidity of aerial sensors during data collection in bracken fern mapping. As a result of sparse bracken fern configurations visual inspection and photo interpretation becomes tedious, error prone and time consuming (Drake 2000). Therefore, the accuracy and quality of the research findings requires high level of expertise of the interpreter. Efficient remote sensing of invasive species such as bracken fern requires a considerably bulky study area. Large sized plots typically require field validation ~~for~~ of the ~~analysis~~, this would however make sampling complex in uneven terrain landscapes (Jönsson and Eklundh 2004). Additionally the cost for labor and time are unaffordable for data validation analysis (Huang and Geiger 2008).

2.7 Possible future prospects in remote sensing of bracken fern weeds

Empirical evidence shows that for the past few decades significant improvements have been achieved in the adoption of efficient remote sensing approaches to discriminate and monitor spatial and temporal distribution of bracken fern (Singh *et al.* 2014; Odindi *et al.* 2014). However, it is also clear that there are still more aspects to be explored as far as remote sensing of bracken fern is concerned. Future research on remote sensing of bracken will specifically focus on the utilization of high quality three-dimensional canopy reflectance modeling capabilities. A comprehensive canopy data that would have been captured during the course of the stages of bracken canopy life cycle will be used for modeling and predicting the risk of future invasions. Another area which can be explored in bracken fern research is super-resolution analysis ~~of the invasive plant~~. Super resolution analysis can utilize new sophisticated techniques and processing algorithms (Atkinson 2009; Park *et al.* 2003). The mentioned techniques have the ability to significantly improve bracken fern classification accuracy. In most developing nations, South Africa for example, very few ~~research~~ studies have used hyperspectral remote sensing techniques for vegetation mapping because of high cost and poor accessibility of the remote sensing imagery (Odindi *et al.* 2014). There is still need for more hyperspectral remote sensing research on bracken fern spatial distribution sightseeing biochemical and biophysical restrictions using innovative progression based models.

Supplementary effort is required to adopt ~~advanced~~ improved bracken classification applications to advance the precision of mapping bracken fern. Additionally, future research could assist in gaining essential understanding of the similarities and differences in bracken reflectance quantities and other vegetation classes. The influence of properties such as leaf area index, biomass, pigment concentration and nitrogen on bracken reflectance patterns could be investigated. New developments in scientific exploration in remote sensing capabilities now advocating for possible launching of innovative robust systems being established to manipulate biochemical and biophysical spectral data for vegetation mapping (Ustin and Gamon 2010; Cochrane 2000).

Since retrieval of bracken reflectance has been problematic due to hill shading, numerous studies have used digital elevation models to predict bracken spatial distribution in mountainous areas (Curatola Fernández *et al.* 2015; Göttlicher *et al.* 2009). A number of digital elevation models and algorithms for advanced topographic correction have been used, however to date the majority of them have not been appropriately assessed (Riaño *et al.* 2003; McDonald *et al.* 2002). The aforementioned researchers profoundly took into consideration a restricted set of lighting conditions. Therefore, various topographic correction procedures for multiple remote sensing images acquired at different seasons under various terrain conditions could be a good precedent for future research. The review has discovered that current research studies on remote sensing of bracken fern have few works that have investigated multi-temporal remote sensing of bracken fern to improve understanding of the spatial distribution of bracken fern over time (Curatola Fernández *et al.* 2015; Schneider and Fernando 2010). Therefore there is need for researchers to engage long term monitoring and seasonal mapping of the weeds at a larger scale. Long term remote sensing applications are predicted to be fruitful in the determination of spatial trends and evolution of bracken fern distribution over a long period of time.

2.8 Conclusion

The current study has reviewed previous studies on the prospective of remote sensing applications in bracken fern mapping. Empirical evidence have shown that the use of field surveys in mapping spatial distribution, the spread, its life cycle and fern status of bracken fern, remains a challenge in remote parts of the world. Remote sensing technology offers better prospects in detection and mapping the spatial configuration of bracken fern species. The use of medium spatial resolution in detection and mapping the spatial configuration of bracken fern has been constrained by satellite sensor's limited spatial, spectral and radiometric resolution. So far, studies on remote sensing of bracken fern have widely used the freely available medium resolution Landsat series data (Landsat MSS, ETM and ETM+). Although the application of high spatial and spectral resolution sensors have accurately detected and mapped spatial configuration of bracken fern at a local scales, the application of these data sets is inhibited by smaller swath width, low temporal resolution and high acquisition costs. Challenges encountered in remote sensing of bracken fern include problem of similarity in spectral signatures of bracken and other vegetation species leading to low classification accuracy and inflexibility of airborne sensors in data collection. The classification of bracken fern in mountainous areas has been distorted by high cloud frequency, hill shading and poor satellite signal. In future, some of these challenges can be minimized by the use of robust algorithms for classification and complex digital elevation models for topographic normalization.

Chapter Three

Detection and mapping the spatial configuration of bracken fern weeds using the Landsat 8 OLI new generation sensor.

This chapter is based on:

Matongera, T., Mutanga. O, and Dube. T (under review): *Detection and mapping the spatial configuration of bracken fern species using the Landsat 8 OLI new generation sensor*. International Journal of Applied Earth Observation and Geoinformation, Manuscript number: JAG-D-16-00454

Abstract

Bracken fern is an invasive plant that presents serious environmental, ecological and economic problems around the world. An understanding of the spatial distribution of bracken fern weeds is therefore essential for providing appropriate management strategies at both local and regional scales. The aim of this study was to assess the utility of the freely available medium resolution Landsat 8 OLI sensor in the detection and mapping of bracken fern in the Cathedral Peak, South Africa. To achieve this objective, the results obtained from Landsat 8 OLI were compared with those derived using the costly and high spatial resolution WorldView-2 imagery. Since previous studies have already successfully mapped bracken fern using high spatial resolution WorldView-2 image, the comparison was done to investigate the magnitude of difference in accuracy between the two sensors in relation to their acquisition costs. In evaluating the performance of Landsat 8 OLI in discriminating bracken fern compared to that of Worldview-2, we tested the utility of (i) spectral bands; (ii) derived vegetation indices as well as (iii) the combination of spectral bands and vegetation indices based on discriminant analysis classification algorithm. After resampling the training and testing data and reclassifying several times (n= 100) based on the combined data sets, the overall accuracies for both Landsat 8 and WorldView-2 were tested for significant differences based on Mann-Whitney U test. The results showed that the integration of the spectral bands and derived vegetation indices yielded the best overall classification accuracy (80.08% and 87.80% for Landsat 8 OLI and WorldView-2 respectively). Additionally, the use of derived vegetation indices as a standalone data set produced the weakest overall accuracy results of 62.14 % and 82.11% for both the Landsat 8 OLI and WorldView-2 images. There were significant differences $\{U (100) = 569.5, z = -10.8242, p < 0.01\}$ between the classification accuracies derived based on Landsat OLI 8 and those derived using WorldView-2 sensor. Although there were significant differences between Landsat and WorldView-2 accuracies, the magnitude of variation (9%) between the two sensors was within an acceptable range. Therefore, the findings of this study demonstrated that the recently launched Landsat 8 OLI multispectral sensor provides invaluable information that could aid the long term continuous monitoring and formulation of effective bracken fern management frameworks in productive mostly productivity rangelands.

Keywords: Bracken fern, Classification accuracy, Invasion, Remote sensing, Discrimination, Encroachment, Local and regional scales, Rangeland productivity

3.1 Introduction

Invasive species encroachment into grass dominated landscapes has been observed in many parts of KwaZulu-Natal Province in South Africa (O'Connor 2005). Bracken fern is one of the most common invasive species prevalent in KwaZulu-Natal province and other parts of the country (Singh *et al.* 2014). The fern has instigated severe environmental impacts, such as disturbing water distribution patterns (Ester and Al 2016), threat to biological diversity (Schneider, 2006) and disturbance of ecosystem function (Mooney, 2000). Research has revealed that bracken fern intercepts fifty percent of the rainfall, obstructing water from reaching the soil below (Williams 2011). The reduction in optimal water supply threatens productivity of indigenous plant species, particularly in areas that are already experiencing water shortages. Apart from its environmental impacts, bracken fern encroachment has long been an unwelcome weed in farming areas (Turner *et al.* 2016; Berget *et al.* 2015; Schneider and Geoghegan 2006). The emerging threats from uncontrolled spread of bracken fern in South Africa, particularly around the Cathedral Peak vegetation community and its value as a World Heritage Site ascertains the necessity to quantify the spatial distribution and encroachment of bracken to improve appropriate intervention strategies. Lately, remote sensing technology has emerged as a reliable approach for invasive species mapping. The need for consistent assessment of invasive species using remote sensing data has increased in recent years through developments in the understanding of vegetation spectral reflectance properties (Blackburn and Pitman 2010).

Remote sensing technology offers better prospects in providing up to date spatial data required to understand the spread and spatial configuration of bracken fern species (Ngubane 2014). Recent studies have revealed that high spatial resolution sensors can accurately classify bracken fern because of their improved spectral and spatial resolutions (Singh *et al.* 2014; Odindi *et al.* 2014; Ngubane 2014). The applications of high spatial resolution satellite imagery, such as WorldView-2 in the detection and mapping of bracken fern has successfully yielded excellent accuracy results. For example ~~the~~ a study by Odindi *et al.* (2014) reported a good overall accuracy of 84.72%. Similarly, Ngubane (2014) observed that the use of WorldView-2 data characterized by higher spatial resolution improved the accuracy of bracken fern mapping within eThekwini Metropolitan, KwaZulu-Natal, South Africa. Apart from its fine 2m spatial resolution, WorldView-2 has strategically located spectral bands such as red edge, NIR2, coastal and yellow which could avail critical information required in discriminating vegetation (Mutanga *et al.* 2015). However, WorldView-2 sensor may not be appropriate sensor for mapping invasive species in developing regions such as Southern Africa. This is due to its high acquisition costs, small swath width and a limited multi-temporal data which is insufficient for continuous monitoring of the affected landscapes at a regional scale.

The rate at which bracken fern extents globally is still not clearly understood because of the scarcity of high spatial resolution sensors with a regional swath width. These limitations have of late resulted in a shift towards the use of free-and-readily available broadband multispectral sensors with a global footprint (large swath width) and a higher repeated coverage, such as the Landsat series datasets (Dube and Mutanga 2015). Moreover Landsat datasets permit repeated regional scale mapping and monitoring. For instance, Dube *et al* (2015) concluded that the Landsat 8 OLI sensor's 16 day temporal resolution it one of the key primary data sources highly suitable and practical for regional applications especially in resource-limited areas. It is upon this background, that considering their accessibility at a global scale, Landsat series products have the potential to provide indispensable data sources for continuous detection and mapping of invasive species over time and space. In this regard, an affordable, efficient and repeatable method of surveying bracken fern invasion enables its monitoring at a regional scale.

The capability of the recently launched Landsat 8 OLI sensor with improved collection of spatial, spectral, temporal and radiometric resolutions combined with its post-launch calibration is hypothesized to offer a great potential in bracken fern mapping. Landsat 8 OLI imagery delivers an improved spectral range of certain bands that are critical for distinguishing vegetation spectral responses across the near infrared (NIR) and panchromatic band. The sensor's enhanced radiometric resolution from 8 bits to 12 bits is crucial in the characterization of different seasonal phenological patterns of vegetation (Dube and Mutanga 2015; El-Askary *et al.* 2014). Landsat 8 OLI has a total of 11 spectral bands captured at a 16 day interval, hence providing a continuous seasonal coverage of the global landmass at a spatial resolution of 30 meters. Additionally, a significant advancement in the sensor design has also enriched substantial improvements in signal to noise ratios (SNR), almost twice as good as Landsat 7 Enhanced thematic mapper plus (Dube and Mutanga 2015; Irons *et al.* 2012). Landsat 8 OLI data set has been successfully used in various remote sensing studies including water resources management (Shoko *et al.* 2015b; Shoko *et al.* 2015a), biomass studies and crop yield (Dube and Mutanga 2015; Hurley *et al.* 2014; Crippen 1990). The successful application of Landsat 8 OLI sensor in different studies has also been largely accomplished by the use of vegetation indices, such as the normalized difference vegetation index (NDVI) computed from the red and near infrared bands (Mutanga *et al.* 2012). The above mentioned indices respond to the difference in the chlorophyll absorption levels as a result of multiple scattering effects in the near infrared (Thenkabail *et al.* 2000). However, the same approach of combining derived vegetation indices and spectral bands can also be tested in bracken fern mapping using the medium spatial resolution Landsat 8 OLI sensor.

Therefore, considering the sensor's performance in vegetation mapping, due to the aforementioned sensor's improvements, it is hypothesized that the freely available Landsat 8 OLI sensor with improved sensor characteristics has the potential to detect and map the spatial distribution of bracken fern with acceptable accuracies that are comparable to high spatial resolution WorldView-2 sensor. To assess the performance of Landsat 8 OLI data in mapping the invasive bracken fern, we compared its classification performance to that of high resolution WorldView-2 sensor. WorldView-2 data was used to bench-mark the performance of Landsat 8 OLI in this study due to its proven track record of high accuracy in detecting and mapping bracken fern (Odindi *et al.* 2014; Ngubane 2014). To the best of the researcher's knowledge, no study has compared the performance of the medium spatial resolution Landsat 8 OLI with a high resolution sensor, such as WorldView-2 in bracken fern mapping. In this study, for the first time the researcher assessed the utility of the Landsat 8 OLI sensor in detecting and mapping the spatial configuration of bracken fern species in Cathedral Peak, South Africa.

3.2 Materials and Methods

3.2.1 Description of the study area

The research was conducted at Cathedral Peak nature reserve, in KwaZulu-Natal Northern Drakensberg mountain range, South Africa (Figure 3.1). The study site is located at NW= -28.97360039, NW Long= 29.20739937, SE Lat = -29.01429939; SE, Long= 29.2670020.The study area has 15 catchments delineated for research management purposes. The Cathedral Peak nature reserve occupies approximately 32 000 hectares. At an altitude of 3,482 m, the Drakensberg is the highest mountain range in South Africa, extending its mountain ranges to a distance of about 1, 000km from south-west to north-east (Rosen *et al.* 1999). The mountains being further away from the equator~~,~~ is characterize by cooler habitats at lower altitudes than most mountain ranges in southern Africa (Condie and Kröner 2008). The area is characterised by a diversity of habitats which is split between moderately undulating Drakensberg Moist Foothill and grassland plateau (at roughly 1750m asl) leading to densely forested (Figure 3.2) south and east facing slopes. The area is characterised by homogenous basalt formations of stormberg series (Killick 1963). The climate of the area is mainly subtropical, with humid and warm summers, mild winters, and a relatively high amount of rainfall of approximately 950mm per annum. Mean temperatures in summer are around 17^0 C whilst winter is normally around 9^0C. Approximately, ~~70~~ seventy different types of ferns have been documented in the Drakensberg region (Sycholt 2002). Bracken fern (*Pteridium Aquilinum*) is the most common fern in the Cathedral Peak which is often found in grasslands and along forest margins in the montane and sub-alpine belts. With the abundance of vegetation communities in the Drakensberg mountain range, the Cathedral peak specifically is a perfect region in which to study conceivable vegetation changes and shifts, as a consequence of changes in environmental conditions (Adjorlolo *et al.* 2013).

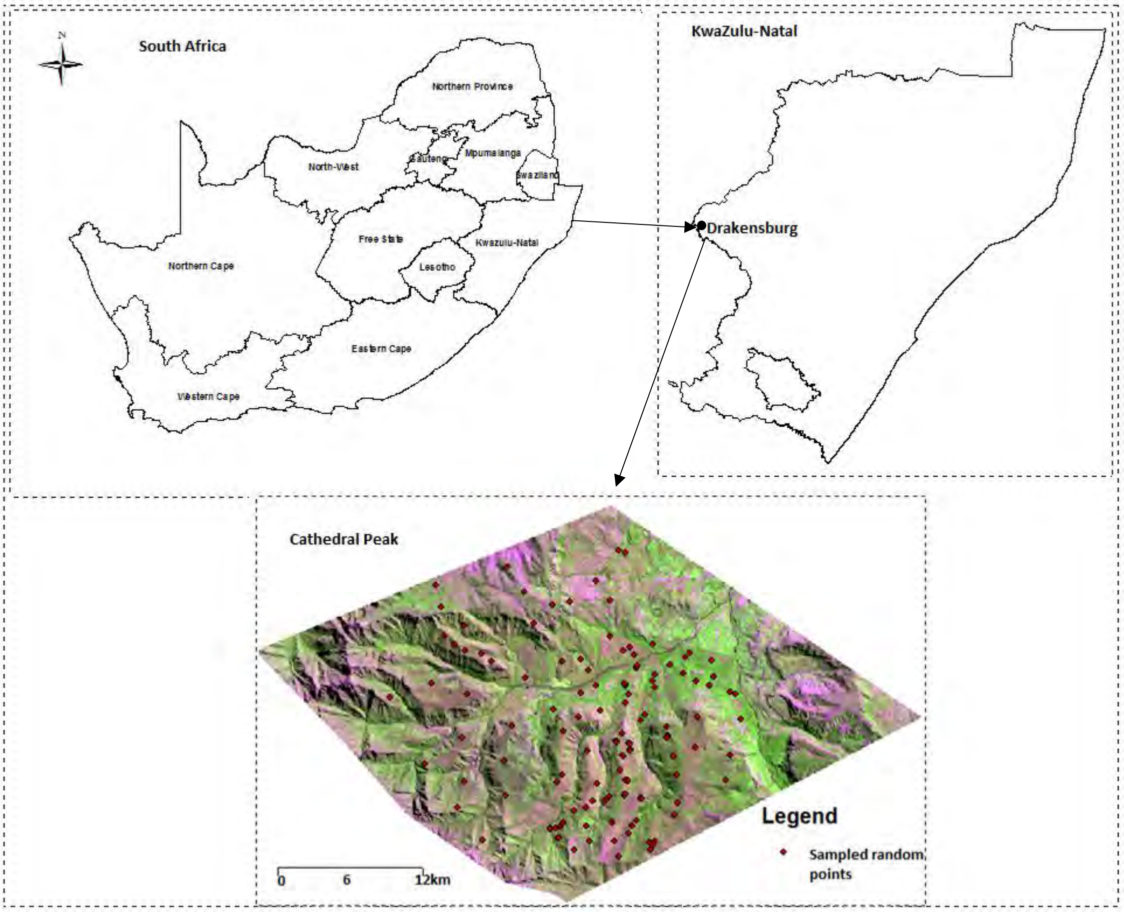

Figure 3.1**:** Location of the study area in Cathedral Peak, Drakensburg in South Africa

Figure 3.2**:** Typical Cathedral Peak field site showing (a) landscape covered with bracken fern (b) bracken fern appearance in summer (c) grassland and shrubs landscape

3.2.2 Field data collection and preprocessing

Extensive reference data was collected to compliment remote sensing data and to perform accuracy assessment. The ground truth data collection was conducted to record the location of bracken fern and other land cover classes, using a hand held Leica GS20 Global positioning system (GPS) with a sub meter accuracy. The field data collection was primarily conducted from the 14th to the 16th of February 2016. The field data was collected on the period that coincide with image acquisition dates. ArcGIS was used to generate stratified random transects from Cathedral peak shape file. Transects were spread all over the 15 delineated catchments in the study area. Transect co-ordinates were subsequently uploaded into a GPS that was used to navigate to the field sites. Systematic sampling procedure was adopted. After every 10m, a quadrant (50cm^2) was measured within the 30m transect. The other land cover (LC) classes which ~~were~~ identified and their locations recorded include grassland, shrubs, settlement and bare patches. The bracken fern GPS-measured locations were recorded in a table format were then converted into point map in a geographic information system.

3.2.3 Remote sensing data acquisition and preprocessing

Landsat 8 OLI tile (path/row: 169/80) covering the study area was acquired. Landsat 8 OLI sensor is a combination of two pushbroom instruments: (i) the Operational Land Imager (OLI) consisting of nine spectral bands (refer to Table 3.1) and (ii) the Thermal Infrared Sensor (TIRS) which encompasses thermal bands 10 and 11 at a 100 m spatial resolution. The resolution for Band 8 (panchromatic) is 15 meters. All bands can collect one of two gain settings (high or low) for increased radiometric sensitivity and dynamic range, while Band 6 collects both high and low gain for all scenes. Approximate scene size is 170 km north-south by 183 km east-west (106 mi by 114 mi). Landsat 8 OLI imagery covering the region of interest was acquired during the time that coincided with ground truth data collection dates. The image was acquired during a sunny and clear sky day conditions with very little cloud cover of about 1.06%, sun azimuth angle of 50.14 and sun elevation angle of 50.29. The image was accessed from the USGS Earth Resources Observation and Science (EROS) Centre archive (http://earthexplorer.usgs.gov/) on the 15th of February 2016. For comparison purposes, WorldView-2 imagery covering the study area was also acquired on the 16th of February 2016 from DigitalGlobe. WorldView-2 has strategically positioned eight multispectral bands that assist in analyzing important vegetation applications. The imagery has a swath width of about 16.4km and frequent revisit intervals of 1.1 days. The sensor acquires 11 bit-data in eight multispectral bands (Ghosh and Joshi 2014). The image was orthorectified and geometrically corrected by DigitalGlobe. Prior to any analysis, the Landsat 8 OLI and WorldView-2 satellite images were pre-processed using the Fast Line of Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) based on the parameters issued with the image. The analysis was conducted after converting the image into radiance in the ENVI 4.1 platform.

Table 3.1**:** Landsat 8 OLI and WorldView-2 spectral characteristics used in this study

Landsat 8 OLI spectral bands			WorldView-2 multispectral bands		
Band#	Bandwidth (um)	GSD (m)	Band#	Bandwidth (um)	GSD (m)
2 (Blue)	0.450 – 0.515	30	1 (Coastal blue)	400-450	2
3 (Green)	0.525 – 0.600	30	2 (Blue)	440-510	2
4 (Red)	0.630 – 0.680	30	3 (Green)	520-580	2
5 (NIR)	0.845 – 0.885	30	4 (Yellow)	585-625	2
6 (SWIR)1	1.560 – 1.660	30	5 (Red)	630-690	2
7 (SWIR)2	2.100 – 2.300	30	6 (Red Edge)	705-745	2
8 (Panchromatic)	0.500 – 0.680	15	7 (NIR 1)	770-895	2
			8 (NIR 2)	860-1040	2

(NIR=Near Infrared; SWIR= Short-wave Infrared)

3.2.4 Landsat 8 OLI and WorldView-2 spectral and vegetation indices retrieval

The study computed NDVI-based vegetation indices from all possible two band combinations of Landsat 8 OLI (n=7) and WorldView-2 bands (n=8). NDVI was chosen following its successful application in biomass and crop yield estimation studies (Mutanga *et al.* 2012; Mutanga and Skidmore 2004; Thenkabail *et al.* 2000). An overlay was conducted between the point map of field-measured bracken locations and all the remotely sensed data and their derivatives, in ArcGIS. The extracted values combined with all vegetation indices (n=56) were then exported from a GIS as a table. Discriminant Analysis (DA) algorithm was then used to discriminate bracken fern from other land cover types based on the three analysis stages presented in Table 3.2.

Table 3.2: Landsat 8 OLI, WorldView-2 spectral bands and computed vegetation indices

Applied Variables	**List of Variables**	**Analysis stage**
Spectral bands	Landsat 8: Blue, green, red, near infrared, SWIR 1, SWIR2 and Panchromatic (n=7). WorldView-2: Coastal blue, Blue, Green, Yellow, Red, Red Edge, NIR 1, NIR 2 (n=8).	I
Vegetation indices	Normalised Difference Vegetation Index: NDVIs (n=56)	II
Spectral bands and vegetation indices	Landsat 8 bands (n=7) + NDVIs (n=56) WorldView-2 (n=8) + NDVIs (n=56)	III

3.2.5 Descriptive Statistical data analysis

Using descriptive statistical analysis, we conducted a Kolmogorov Simonov test of normality to assess whether the spectral signatures of bracken fern and other land cover types significantly ($\alpha = 0.05$) deviated from the normal distribution. Following the normality test which indicated that the data did not significantly deviate from the normal distribution ($p > 0.05$) we used analysis of variance to test whether there are any significant differences between bracken fern weeds and other land cover classes under investigation based on spectral data derived.

3.2.6 Image classification and accuracy assessment

The spectral signatures of bracken fern were discriminated from that of other land cover types based on Discriminant Analysis (DA) algorithm. Discriminant analysis is a multivariate statistical modelling technique for classification (Fernandez 2002). The DA was chosen because of its ability to model and predict classification based on the performance of continuous variables in separating specified categories in the classification process. Several research studies have successfully used the DA model in discriminating different land cover classification (Ju *et al.* 2003; Fraley and Raftery 2002; Sibanda *et al.* 2015; Beck *et al.* 1997). As presented in Table 3.2, the first analysis was based spectral bands for Landsat 8 and WorldView-2 images separately. The second analysis computed based on possible NDVI vegetation indices as a stand-alone data set. The final analysis stage incorporated vegetation indices and spectral bands for the two images. Based on the combined data set, the importance of specific spectral bands and derived vegetation indices was tested. All possible band combinations involving Landsat 8 OLI seven bands, and WorldView-2 eight bands were imported into the DA model. The variable correlations were used to identify and rank the optimal variables for detection and mapping of bracken fern. For the validity and reliability of the results, accuracy assessment was performed for each class. Accuracy assessment was conducted based on the results generated by the DA algorithm. For each analysis stage, the acquired classes were cross tabulated on confusion matrix against the ground truth classes for the corresponding pixels on a confusion matrix to determine classification accuracy (Yu *et al.* 2014). Agreement between classification results and ground truth data was measured using the producer accuracy (PA), user accuracy (UA) and overall accuracy (OA) generated from the confusion matrices.

To evaluate the magnitude of difference between Landsat 8 OLI data accuracy and that of WorldView-2 in discriminating bracken fern, we resampled the training and testing datasets in Statistica 13.0 a hundred times using the data from the two sensors. Consequently, we reclassified the data a hundred times. Overall accuracies derived from reclassifying the Landsat 8 OLI and WorldView-2 data were recorded and used for further comparison tests. Specifically, the overall accuracies of data were tested for normality based on the Shapiro Wilk test prior to the comparison analysis. The Shapiro Wilk test indicated that the data significantly ($p < 0.05$) deviated from the normal distribution. Subsequently, a non-parametric Mann-Whitney U test was used to test for significant differences between Landsat 8 and Worlview-2 accuracies. Finally, Landsat 8 OLI and WorldView-2 maps were produced, illustrating the spatial distribution of bracken fern in Cathedral Peak nature reserve.

3.3 Results

3.3.1 Descriptive statistics

Results from the Analysis of variance (ANOVA) test indicated that the mean reflectance of bracken fern was significantly different ($\alpha < 0.05$) from other land cover classes under study. Therefore, the descriptive statistical analysis results showed that the classes are separable as illustrated by Figure 3 (a) and (b). Spectral responses for most of the classes are spectrally distinct in the near infrared (NIR) in both sensors. There was lack of discriminatory potential of bracken fern from grassland based on Landsat 8 OLI blue and green regions of the electromagnetic spectrum. Bracken fern was more spectrally distinct from other classes in the red band.

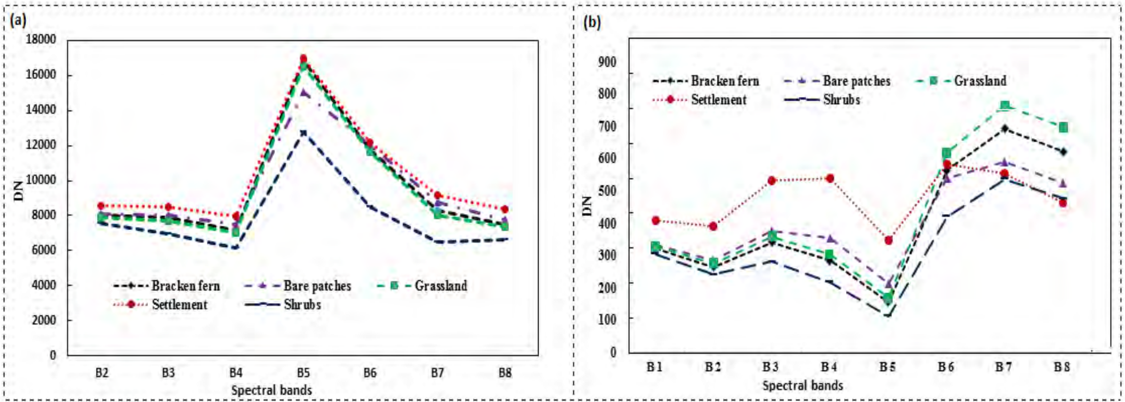

Figure 3.3: Average spectral response for five Land cover classes under study using (a) Landsat 8 OLI (b) WorldView-2 sensor

3.3.2 Image classification

3.3.2.1 Analysis I: Classification results using spectral bands as an independent data set

Land cover classification results obtained using Landsat OLI and WorldView-2 spectral bands as an independent data set are shown in Table 3.3 and Table 3.4. The results indicated that the use of the freely available medium resolution Landsat 8 OLI spectral bands yielded good classification results with an overall accuracy (OA) of 76.02%. Comparatively, the high spatial resolution WorldView-2 sensor was slightly superior in detecting bracken fern with an OA of 82.93%. Correspondingly, good user accuracy in some of the class results (above 75%) were also achieved by OLI sensor. Bracken fern specifically had 95.40% user accuracy compared to

77.01% for Landsat 8 OLI. Of all the five classes, settlement achieved the highest producer and user accuracies using WorldView-2 sensor whilst shrub class achieved the best user and producer accuracies using Landsat 8 OLI. Grassland class produced the least PA and UA results as low as 45.68% UA in WorldView-2 sensor. On average, producer accuracies were generally higher than user accuracies by 4.8% and 3.5% for WorldView-2 and Landsat 8 OLI respectively. Landsat 8 OLI sensor results showed that bracken fern spectral reflectance is similar to that of grassland, especially in the visible part of the electromagnetic spectrum, as evidenced by figure 3.3. WorldView-2 derived spectral bands demonstrated high potential of discriminating bracken fern than medium resolution Landsat 8 OLI by 6.9%.

3.3.2.2 Analysis II: Classification results using derived vegetation indices as an independent data set

Landsat 8 OLI derived vegetation indices performed poorly in detecting and mapping bracken fern with an OA of 62.14%. On the other hand, WorldView-2 derived spectral bands had a considerably high OA of 82.11% (Table 3.3 and 3.4). When compared to analysis I, the overall accuracy decreased by 0.82% and 13.88% for both datasets (WorldView-2 and Landsat 8 OLI respectively). Additionally, Landsat 8 OLI user and producer accuracies also slightly decreased with most of the classes ~~ranging~~ range from 50-65% whilst WorldView-2 maintained an average of 80% in most of the classes. Similar to the previous analysis, grassland scored the lowest producer and user accuracies for both sensors. Grassland had 25.09% UA in Landsat 8 OLI sensor whilst WorldView-2 achieved 52.17%. The results obtained using Landsat 8 OLI and Worldview 2 derived vegetation indices alone produced slightly lower classification accuracies when compared to the use of spectral bands as an independent dataset. Despite the decrease in accuracy in other classes, the classification accuracy for shrubs was above 85% in both sensors. Most notably, bracken fern scored a high user accuracy of 86.20% and 100% for Landsat 8 OLI and WorldView-2 respectively. The difference with regards to magnitude of performance using vegetation indices as an independent data set between the two sensors was 19.9%.

3.3.2.3 Analysis III: Classification results using spectral bands combined with vegetation indices

The results in Table 3.3 and 3.4 shows classification accuracies obtained using Landsat 8 OLI and Worldview 2 derived spectral bands and vegetation indices. Overall, the integration of spectral band information and vegetation indices from the two sensors yielded high classification results in this study. For example, using the combined data set, Landsat 8 OLI and WorldView-2 produced high overall accuracies of 80.08% and 87.80% respectively. Landsat 8 OLI sensor performed slightly weaker than WorldView-2 sensor. Results for specific classes, such as grassland shows that both producer and user accuracy results which was previously ranging below 50% increased by more than 15% in both sensors. Of all the three analysis conducted, settlement class obtained the highest PA results of 100% in WorldView-2. The use of integrated dataset significantly improved Landsat 8 OLI classification results by 17.94%, when compared to the use of vegetation indices as an independent dataset. Similarly, Worldview-2 attained a slight increase of 5.69% when compared to the use of spectral bands as independent dataset and 4.87% when compared to the use of vegetation indices as an independent data set. Additionally, the results from the final analysis established a significant improvement on the user, producer and overall accuracies for all classes incorporated in this study. Generally, the integration of spectral bands and vegetation indices led to significant increase in producer, user and overall accuracies from both Landsat 8 OLI and Worldview 2 sensors.

The Shapiro Wilk normality test results revealed that the overall accuracies derived based on the two sensors were not normally distributed; Landsat 8 (Shapiro-Wilk W= 0.86203, $p < 0.05$) and WorldView-2 (Shapiro-Wilk W=75915, $P < 0.05$). Figure 3.4 illustrates the normality distribution test results for the two sensors.

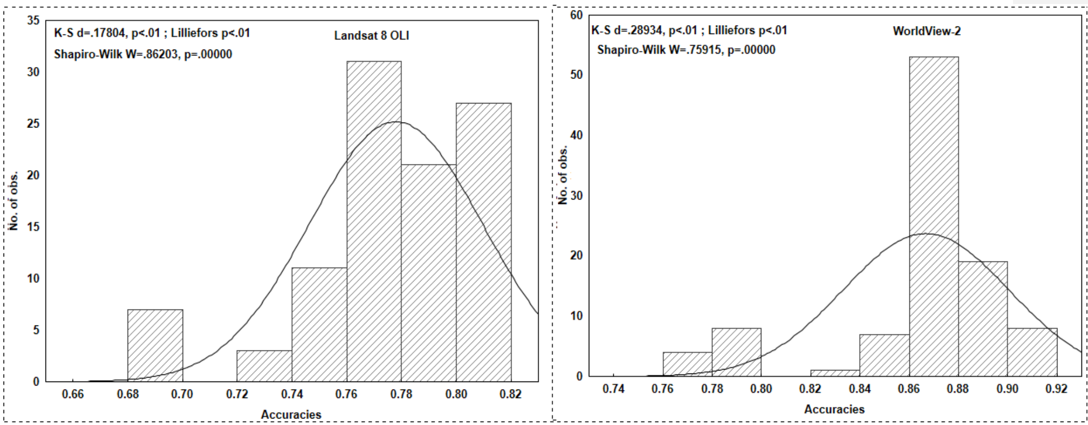

Figure 3.4 Shapiro Wilk normality distribution for Landsat 8 and WorldView-2

The Mann-Whitney non-parametric test revealed that overall accuracies from the two sensors differed significantly from each other with U (100) = 569.5, z = -10.8242, $p < 0.01$. The median overall accuracies were 78% and 87% for Landsat 8 OLI and WorldView-2 sensors as illustrated in Figure 3.5. Although there were significant differences between Landsat 8 and WorldView-2, the magnitude of variation (9%) between the two sensors was small and it can be considered to be within an acceptable range.

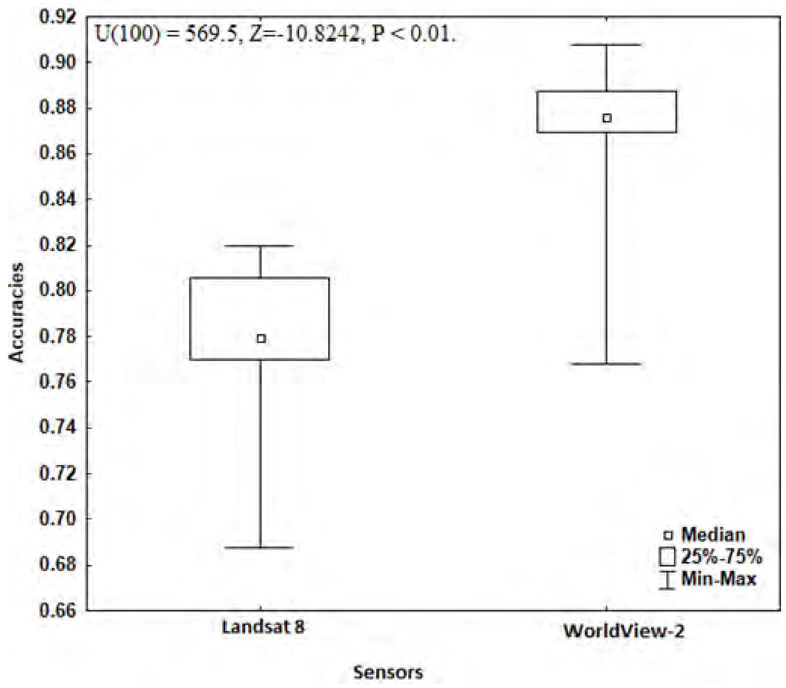

Figure 3.5 Mann-Whitney box plots for Landsat 8 OLI and WorldView-2 sensors.

3.3.2.4 Variable ranking based on the combined data set

For Landsat 8 OLI, five variables (n=5) ~~were~~ identified as the best in detecting and mapping bracken fern were the NDVIs which produced the highest eigenvalues. These were calculated using a combination of bands SWIR2/Red, SWIR1/Red, SWIR1/ SWIR2, NIR/Red and NIR/SWIR2. On the other hand WorldView-2 variable ranking (n=5) reported spectral bands which lie in the near infared 1 (770-895nm), red edge (705-745nm), near infrared 2 (860-1040nm) and NDVIs calculated from a combination of bands NIR/red and red edge/green.

Therefore, the data set from the optimal variables was used to compute a model that produced classfication maps (Figure 3.5 a and b).

Table 3.3: Bracken fern classification accuracies (%)

	Analysis I			Analysis II			Analysis III		
	PA	UA	**OA**	PA	UA	OA	PA	UA	OA
Landsat 8	73.62	77.01	**76.02**	55.81	86.20	**62.14**	72.64	75.00	**80.08**
WorldView-2	76.14	95.40	**82.93**	71.10	100	**82.11**	82.17	95.40	**87.80**

(PA= Producer Accuracy, UA= User Accuracy and OA =Overall Accuracy)

Table 3.4: Landsat 8 and WorldView-2 accuracies (%) for other land cover classes.

Landsat 8	Analysis I		Analysis II		Analysis III		WV-2 Analysis 1		Analysis II		Analysis III	
	PA	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**
Bare	73.33	61.11	51.02	58.33	71.05	88.51	80.00	88.89	82.35	77.78	86.11	86.11
Grass	66.07	80.43	80.72	25.09	88.23	65.22	87.5	45.68	88.88	52.17	87.17	73.91
Settlement	54.37	71.05	73.66	87.10	87.5	89.74	100	89.47	100	84.21	100	92.11
Shrub	91.89	87.18	88.08	37.64	92.22	73.68	87.17	87.18	96.87	79.49	94.28	84.62
OA	**76.02**		**62.14**		**80.08**		**82.93**		**82.11**		**87.80**	

(PA= Producer Accuracy, UA= User Accuracy and OA =Overall Accuracy)

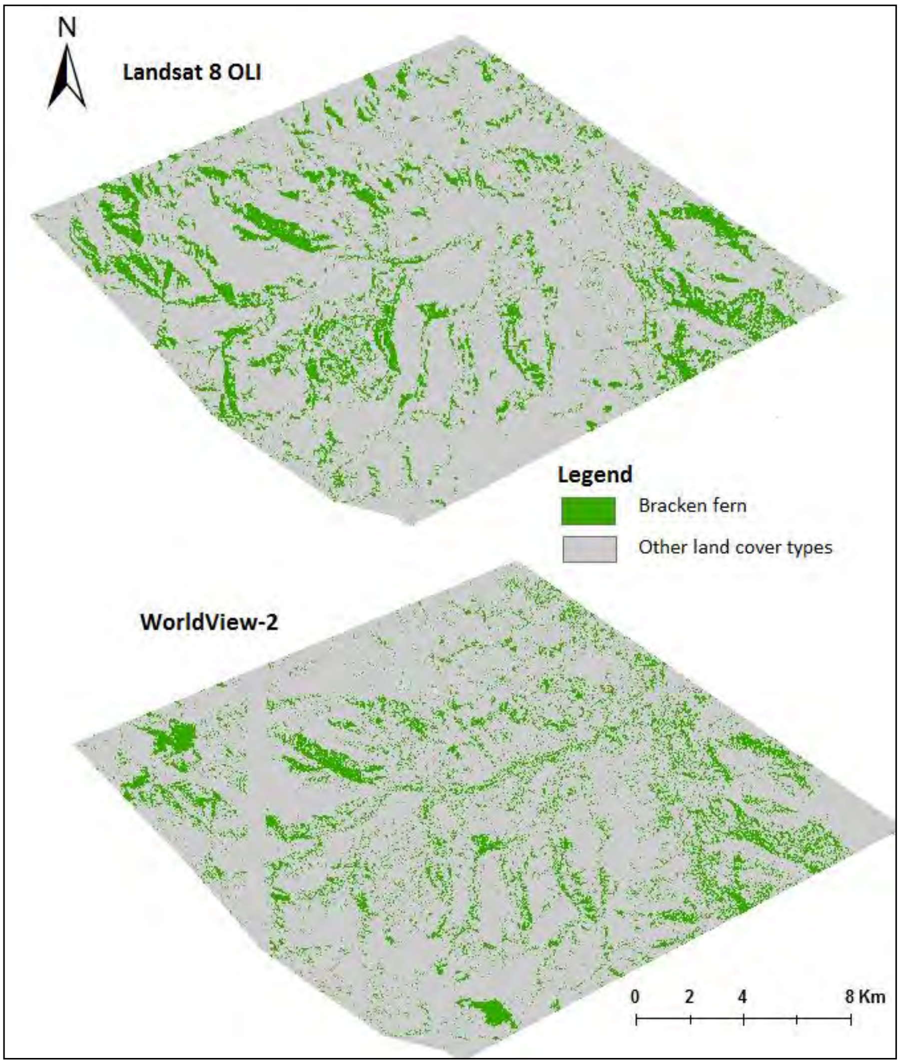

Figure 3.6: Land cover classification maps for Landsat 8 OLI and WorldView-2 obtained based on the classification models derived from analysis III results for Landsat 8 OLI and WorldView-2.

3.4 Discussion

The results of this study demonstrated that the freely available Landsat 8 OLI multispectral sensor has the ability to detect and map bracken fern with overall accuracy results that are comparable to high spatial resolution WorldView-2. For example, the use of raw spectral bands combined with vegetation indices derived from Landsat 8 OLI yielded high overall classification accuracy of 80.08%. The observed results are almost comparable to those obtained using the same variables derived from the high spatial resolution WorldView-2 sensor which yielded slightly higher overall classification accuracy of 87.80%. The magnitude of difference in performance between the two sensors after a series of repeated classifications revealed that the difference in accuracy was small (9%). The comparable performance of Landsat 8 OLI in detecting and mapping spatial configuration of bracken fern can be attributed to the distinctive sensor design. For example the Landsat 8 OLI utilizes numerous elongated sets of detectors for each waveband capable of a detailed scan of the surface along track (Dube and Mutanga 2015). Therefore, the along track function enhances the sensitivity of the sensor to most critical vegetation biophysical metrics. Additionally, the existence of a more refined spectral range for particular bands, such as the near-infrared plays a critical role in boosting vegetation spectral responses while the enhanced image radiometric resolution (12 bits) permits accurate detection of different vegetation conditions (El-Askary *et al.* 2014; Pahlevan and Schott 2013). Moreover, extended sensor radiation sampling residence-period for each field-of-view enhances accuracy during spectral detection and this consequently reduces various challenges in vegetation mapping (Jia *et al.* 2014). The aforementioned strength of the freely available Landsat 8 OLI multispectral sensor therefore could explain its optimal performance and hence an alternative for bracken fern mapping when compared to the high resolution costly WorldView-2 sensor especially in data scarce environments.

Furthermore PA and UA results using the combined data set increased significantly when compared to the results previously obtained in preceding stages (analysis I and II), thus an improvement in the ability of the data set variables to discriminate specific classes from others. Since accuracies increased in both sensors after combining spectral bands and NDVIs, the results of the current study therefore, clearly indicate the general importance of combining vegetation indices with spectral bands in the discrimination of bracken fern. The improvement in overall accuracy after combining spectral bands and vegetation indices can be attributed to the ability of vegetation indices to suppress soil background, sensor zenith angle, sun angle and other atmospheric impurities hence when combined with spectral bands increase in terms of performance.

The obtained results concur with ~~previous research findings published by~~ Jia *et al.* (2014) who also reported a unique strength of integrating vegetation indices in discriminating various land cover types. Additionally, ~~previous study by~~ Mushore *et al.* (2016) ~~also~~ demonstrated the potential of the use of raw spectral bands combined with vegetation indices derived from Landsat 8 OLI sensor in classifying urban landscapes. Similar results were also observed when a combination of Landsat 8 OLI extracted spectral information and spectral vegetation indices were used in quantifying aboveground biomass in uMgeni catchment, South Africa (Dube and Mutanga 2015).

Basing on the results observed from combining the data set, Landsat 8 OLI ~~appear to~~ provide a cost effective opportunity for regional scale mapping and monitoring of invasive vegetation species such as bracken fern ~~weeds~~ when compared to high resolution sensors such as WorldView-2 which are costly to data scarce regions, such as Southern Africa. However, this is despite the fact that WorldView-2 has high spatial resolution which facilitates the discrimination of invasive species spectral signature from other vegetation and cover types. Moreover, the application of high resolution ~~remote sensing~~ sensors is associated with several limitations such as cost, availability, spectral processing and analysis complications especially in the sub-Saharan Africa given the financial challenges (Dube and Mutanga 2015; Dube 2012; Mutanga *et al.* 2012). Furthermore, the absence of application of WorldView-2 temporal data sets is a limiting factor in the continuous monitoring of invasive species encroachment into the rangelands. When compared to Landsat 8 OLI, WorldView-2 has a small swath-width limiting its applicability to small areas. Landsat products have the largest swath width of 18km which is suitable for regional assessments. The availability of Landsat data in Geocover dataset and the United States Geological Survey (USGS) and their decision to provide free access to all Landsat data holdings offer great opportunities for multi-temporal mapping of invasive species such as bracken fern at a limited cost.

Although the objective of this study was not to compare different variables in bracken fern classification, the study has shown that the use of derived spectral bands as a standalone data set (Analysis I) in bracken fern classification yielded slightly lower results when compared to the results reported using the combined data set. Overall, although Landsat 8 OLI sensor obtained considerably inferior results when compared to WorldView-2 sensor, the freely available Landsat 8 sensor demonstrated an improved potential in discriminating grassland from bracken fern, this was evidenced by higher producer and user accuracies from the sensor compared to WorldView-2 results. Therefore, despite low overall accuracy results reported ~~in~~ based on the use of spectral bands as an independent dataset, the potential of Landsat 8 OLI spectral bands in discriminating certain land cover classes in vegetation classification cannot be ignored. The importance of Landsat 8 OLI derived spectral bands in detection and mapping of bracken fern weeds demonstrated in this study concur with ~~previous research findings by~~ Pahlevan *et al.* (2014) who also confirmed the significance of Landsat 8 OLI spectral bands in aquatic remote sensing applications.

Research findings from this study have proven that the use of vegetation indices as an independent data set in bracken fern classification produced the weakest accuracy results when compared to those obtained using spectral bands (Analysis I) and the combined data set (Analysis III). Therefore the current study established that the applications of derived vegetation indices as a stand-alone data set in land cover classification is inadequate. On the other hand the results from the current study contradict ~~with~~ previous studies ~~who~~ that reported significant potential of derived spectral vegetation indices in vegetation mapping (Li *et al.* 2013; Schuster *et al.* 2012; Souza *et al.* 2010). According to the test results bare patches had the lowest producer and user accuracies in both sensors during analysis II. The results concurred with research findings by Stathakis *et al.* (2012) who established that the major limitation with these vegetation indices can adequately distinguish bare areas and built up areas since they exhibit similar properties with built up areas. Although not yet tested, based on the findings of this study, it is presumed that if freely available Landsat 8 OLI spectral bands combined with NDVI vegetation indices can be applied in the detection and mapping of bracken fern at a large scale, with optimal accuracies. Additionally, the freely available Landsat data archive will improve continuous monitoring of invasive species spreading. Future research studies should focus on developing robust classification algorithms which can improve accuracy results from freely available Landsat imagery in order to promote multi-temporal mapping of invasive species at a regional scale.

3.5 Conclusion

Based on the findings of this study, we have concluded that the freely available Landsat 8 OLI multispectral sensor can provide a cost effective opportunity for regional scale detection, mapping and monitoring of bracken fern weeds when compared to high resolution sensors such as WorldView-2. In that regard, the findings of this study have shown that:

- The use of Landsat 8 OLI raw spectral bands combined with derived NDVI vegetation indices significantly improved the detection and mapping of bracken fern.
- The freely available Landsat 8 OLI multispectral sensor can provide an affordable opportunity for the detection, mapping and monitoring of bracken fern weeds at a regional scale with acceptable accuracies that are comparable to the costly high spatial resolution WorldView-2 sensor.

Chapter Four

Objectives reviewed and conclusions

4.1 Introduction

The main focus of this research study was to assess remote sensing applications for monitoring the spatial distribution of bracken fern in the Cathedral Peak. In this chapter, the aims and objectives established in the introduction section (Chapter 1) are reviewed against conclusions. The chapter also highlights the major conclusions and recommends potential opportunities for research.

4.2 Objectives reviewed

Objective (1):

To review the progress and challenges in the detection and mapping of bracken fern weeds using multispectral remotely sensed data

Previous research studies on mapping and detecting spatial distribution of bracken fern using remote sensing data have been constrained by spatial and spectral limitations. The study reviewed progress and challenges in the detection and mapping of bracken fern weeds. Remote sensing has proven useful in providing fine spectral and spatial resolution capabilities that are primarily essential to offer precise and reliable data on the spatial distribution of bracken fern. Medium resolution sensors have limited spatial characteristics which constraints the detection of bracken fern, while their high temporal resolution and larger swath width offers a great potential in remote sensing of bracken fern. High resolution sensors such as WorldView-2, IKONOS and Quickbird, with less than 5m spatial resolution can accurately detect the fern, whereas their high acquisition costs, low temporal resolution and smaller swath width remains a huge challenge in detecting spatial configuration of bracken fern at a regional scale. In this regard, since there is no clear benchmark set yet for adequate sensor characteristics in bracken fern mapping, it is recommendable that both medium and high spatial and spectral resolution sensors can be utilized with regards to magnitude of mapping accuracy expected in that specific study and the size of bracken fern's patches. Furthermore, the review has established that major challenges in remote sensing of bracken fern include similarity in spectral signatures of bracken and other vegetation species such as grasses, topographic shading leading to low classification accuracy and inflexibility of airborne sensors in data collection.

Objective (2):

To evaluate the effectiveness of the freely available medium resolution Landsat 8 OLI sensor in detecting and mapping bracken fern

Invasive species widespread is a global phenomenon that requires continuous surveys and monitoring strategies that presents accurate and dependable information. The aim of this study was to assess the utility of the freely available medium spatial resolution Landsat 8 OLI sensor in the detection and mapping of bracken fern. ~~Basing~~ Based on the research findings from this study, the freely available Landsat 8 OLI sensor provided a cost effective opportunity for detecting and mapping of the spatial configuration of bracken fern weeds when compared to high spatial resolution WorldView-2. The magnitude of variation in accuracies between the two sensors was small (9%) which can be considered to be within an acceptable range. However, the performance of Landsat 8 OLI in detecting and mapping spatial configuration of bracken fern can be accredited to the unique sensor design. Specifically, the Landsat 8 OLI sensor utilizes various lengthened sets of detectors for each waveband capable of providing a detailed scan of the surface along track (Dube and Mutanga 2015). Therefore, the along track function enhances the sensitivity of the sensor to most critical vegetation biophysical metrics. Furthermore, the existence of a more refined spectral range for particular bands, such as the near-infrared plays a critical role in boosting vegetation spectral responses while the enhanced image radiometric resolution (12 bits) permits accurate detection of different vegetation conditions (Pahlevan and Schott 2013). Landsat 8 OLI sensor demonstrated a huge potential in continuous monitoring of bracken fern encroachment at a region scale, a previously challenging task with expensive high spatial resolution sensors such as WorldView-2.

4.3 Conclusions

The major aim of this study was to assess remote sensing applications for monitoring the spatial distribution of bracken fern in the Cathedral Peak: Drakensberg, South Africa. ~~Research~~ Findings from the study have shown that despite their spatial and spectral limitations medium spatial resolution sensors such as Landsat 8 OLI can provide invaluable information that could aid the long term monitoring of bracken infested landscapes. These conclusions are consolidated based on the observations throughout this thesis and answers the key research questions mentioned in the introduction chapter:

- **What are the major challenges and opportunities in remote sensing of bracken fern?**

Challenges encountered in remote sensing of bracken fern include problem of similarity in spectral signatures of bracken and other vegetation species leading to low classification accuracy, especially in mountainous areas which are distorted by high cloud frequency and poor satellite signals. Furthermore, the retrieval of bracken fern reflectance is problematic particularly in case of topographic shading. Terrain shadows influence bracken reflectance patterns. However, future opportunities in remote sensing of bracken fern can focus on high computing power and complex high spatial resolution digital elevation models (DEMs) that are required for topographic correction so as to reduce the effects of terrain shadows. Since high spatial resolution sensors have high acqusition costs which contrain continous monitoring of bracken fern, future oppotunites can also investigate the suitability of freely available new generation sensors such as Landsat 8 OLI.

- **Does the freely available Landsat 8 OLI sensor effectively detect and map bracken fern spatial distribution?**

The freely available Landsat OLI multispectral sensor can provide a cost effective opportunity for the detection, mapping and monitoring of bracken fern weeds at a regional scale. Landsat 8 sensor’s 16 day temporal resolution makes the sensor one of the key primary data sources highly suitable and practical for regional applications especially in resource-limited areas. It is upon this background that considering their accessibility at a global scale, Landsat series products have the potential to provide indispensable data sources for continuous detection and mapping of invasive species over time and space.

References

Adam, E., Mutanga, O. & Rugege, D. 2010. Multispectral and hyperspectral remote sensing for identification and mapping of wetland vegetation: a review. *Wetlands Ecology and Management,* 18(3)**,** 281-296.

Adjorlolo, C., Mutanga, O., Cho, M. A. & Ismail, R. 2013. Spectral resampling based on user-defined inter-band correlation filter: C 3 and C 4 grass species classification. *International Journal of Applied Earth Observation and Geoinformation,* 21**,** 535-544.

Aplin, P. 2004. Remote sensing: land cover. *Progress in Physical Geography,* 28(2)**,** 283-293.

Aplin, P. 2005. Remote sensing: ecology. *Progress in Physical Geography,* 29(1)**,** 104-113.

Asner, G. P. & Vitousek, P. M. 2005. Remote analysis of biological invasion and biogeochemical change. *Proceedings of the National Academy of Sciences of the United States of America,* 102(12)**,** 4383-4386.

Atkinson, P. M. 2009. Issues of uncertainty in super-resolution mapping and their implications for the design of an inter-comparison study. *International Journal of Remote Sensing,* 30(20)**,** 5293-5308.

Beck, K. G., Zimmerman, K., Schardt, J. D., Stone, J., Lukens, R. R., Reichard, S., Randall, J., Cangelosi, A. A., Cooper, D. & Thompson, J. P. 2008. Invasive species defined in a policy context: Recommendations from the Federal Invasive Species Advisory Committee. *Invasive Plant Science and Management,* 1(4)**,** 414-421.

Beck, L. R., Rodriguez, M. H., Dister, S. W., Rodriguez, A. D., Washino, R. K., Roberts, D. R. & Spanner, M. A. 1997. Assessment of a remote sensing-based model for predicting malaria transmission risk in villages of Chiapas, Mexico. *The American journal of tropical medicine and hygiene,* 56(1)**,** 99-106.

Berget, C., Duran, E. & Bray, D. B. 2015. Participatory Restoration of Degraded Agricultural Areas Invaded by Bracken Fern (Pteridium aquilinum) and Conservation in the Chinantla Region, Oaxaca, Mexico. *Human Ecology,* 43(4)**,** 547-558.

Birnie, R. 1985. An assessment of the bracken problem in relation to hill farming in Scotland. *Soil Use and Management,* 1(2)**,** 57-60.

Birnie, R. & Miller, D. 1986. The bracken problem in Scotland: a new assessment using remotely sensed data. *Bracken: ecology, land use and control technology, Parthenon Press, New York*.

Blackburn, G. A. & Pitman, J. 2010. Biophysical controls on the directional spectral reflectance properties of bracken (Pteridium aquilinum) canopies: results of a field experiment. *International Journal of Remote Sensing,* 20(11)**,** 2265-2282.

Budreski, K. A., Wynne, R. H., Browder, J. O. & Campbell, J. B. 2007. Comparison of segment and pixel-based non-parametric land cover classification in the Brazilian Amazon using multitemporal Landsat TM/ETM+ imagery. *Photogrammetric Engineering & Remote Sensing,* 73(7)**,** 813-827.

Bunce, R., Barr, C. & Fuller, R. 1992. Integration of methods for detecting land use change, with special reference to Countryside Survey 1990.

Burgiel, S. & Muir, A. 2010. Invasive Species, Climate Change and Ecosystem-Based Adaptation: Addressing Multiple Drivers of Global Change.(Global Invasive Species Programme (GISP); 2010.

Campbell, J. B. & Wynne, R. H. 2011. *Introduction to remote sensing*, Guilford Press.

Chavasse, C. & Davenhill, N. A. 1973. review of chemical control of bracken and gorse for forest establishment. *Proc NZ Weed Pest Control Soc*.

Civco, D. L. 1993. Artificial neural networks for land-cover classification and mapping. *International Journal of Geographical Information Science,* 7(2)**,** 173-186.

Cochrane, M. 2000. Using vegetation reflectance variability for species level classification of hyperspectral data. *International Journal of Remote Sensing,* 21(10)**,** 2075-2087.
Cody, W. J. & Crompton, C. W. 1975. THE BIOLOGY OF CANADIAN WEEDS.: 15. Pteridium aquilinum (L.) Kuhn. *Canadian Journal of Plant Science,* 55(4)**,** 1059-1072.
Condie, K. C. & Kröner, A. 2008. When did plate tectonics begin? Evidence from the geologic record. *Geological society of America special papers,* 440**,** 281-294.
Congalton, R. G. 2001. Accuracy assessment and validation of remotely sensed and other spatial information. *International Journal of Wildland Fire,* 10(4)**,** 321-328.
Conway, E. 1957. Spore production in bracken (Pteridium aquilinum (L.) Kuhn). *The Journal of Ecology***,** 273-284.
Crippen, R. E. 1990. Calculating the vegetation index faster. *Remote Sensing of Environment,* 34(1)**,** 71-73.
Curatola Fernández, G., Silva, B., Gawlik, J., Thies, B. & Bendix, J. 2013. Bracken fern frond status classification in the Andes of southern Ecuador: combining multispectral satellite data and field spectroscopy. *International journal of remote sensing,* 34(20)**,** 7020-7037.
Curatola Fernández, G. F., Obermeier, W. A., Gerique, A., López Sandoval, M. F., Lehnert, L. W., Thies, B. & Bendix, J. 2015. Land cover change in the Andes of Southern Ecuador—Patterns and drivers. *Remote Sensing,* 7(3)**,** 2509-2542.
DeFries, R. S., Asner, G. P. & Houghton, R. 2004. Trade-offs in Land-Use Decisions: Towards a Framework for Assessing Multiple Ecosystem Responses to Land-Use Change. *Ecosystems and land use change***,** 1-9.
Der, J. P., Thomson, J. A., Stratford, J. K. & Wolf, P. G. 2009. Global chloroplast phylogeny and biogeography of bracken (Pteridium; Dennstaedtiaceae). *American Journal of Botany,* 96(5)**,** 1041-1049.
Drake, S. E. 2000. Climate-correlative modeling of phytogeography at the watershed scale.
Dube, T. 2012. Primary productivity of intertidal mudflats in the Wadden Sea: a remote sensing method. *MSc University Twente-ITC, Enschede***,** 27.
Dube, T. & Mutanga, O. 2015. Evaluating the utility of the medium-spatial resolution Landsat 8 multispectral sensor in quantifying aboveground biomass in uMgeni catchment, South Africa. *ISPRS Journal of Photogrammetry and Remote Sensing,* 101**,** 36-46.
Dube, T., Mutanga, O. & Ismail, R. 2016. Quantifying aboveground biomass in African environments: A review of the trade-offs between sensor estimation accuracy and costs. *Topical Ecology,* 57(3).
Dukes, J. S. & Mooney, H. A. 1999. Does global change increase the success of biological invaders? *Trends in Ecology & Evolution,* 14(4)**,** 135-139.
El-Askary, H., Abd El-Mawla, S., Li, J., El-Hattab, M. & El-Raey, M. 2014. Change detection of coral reef habitat using Landsat-5 TM, Landsat 7 ETM+ and Landsat 8 OLI data in the Red Sea (Hurghada, Egypt). *International Journal of Remote Sensing,* 35(6)**,** 2327-2346.
Engelman, H. M. & Nyland, R. D. 2006. Interference to hardwood regeneration in northeastern North America: Assessing and countering ferns in northern hardwood forests. *Northern journal of applied forestry,* 23(3)**,** 166-175.
Ester, W. & Al, R. A. 2016. A guide to managing and restoring wetlands in Western Australia.
Fernandez, G. C. Year: Published. Discriminant analysis, a powerful classification technique in data mining. *Proceedings of the SAS Users International Conference*. 247-256.
Field, C. B., Lobell, D. B., Peters, H. A. & Chiariello, N. R. 2007. Feedbacks of terrestrial ecosystems to climate change*. *Annu. Rev. Environ. Resour.,* 32**,** 1-29.

Fletcher, M. T., Hayes, P. Y., Somerville, M. J. & De Voss, J. J. 2010. Ptesculentoside, a novel norsesquiterpene glucoside from the Australian bracken fern Pteridium esculentum. *Tetrahedron Letters,* 51(15)**,** 1997-1999.

Fletcher, W. & Kirkwood, R. 1979. The bracken fern (Pteridium aquilinum L.(Kuhn)); its biology and control. The experimental biology of ferns. London, Academic Press.

Foody, G. M., Muslim, A. M. & Atkinson, P. M. 2005. Super-resolution mapping of the waterline from remotely sensed data. *International Journal of Remote Sensing,* 26(24)**,** 5381-5392.

Fraley, C. & Raftery, A. E. 2002. Model-based clustering, discriminant analysis, and density estimation. *Journal of the American statistical Association,* 97(458)**,** 611-631.

Fuller, R., Groom, G. & Jones, A. 1994. Land cover map of Great Britain. An automated classification of Landsat Thematic Mapper data. *Photogrammetric Engineering and Remote Sensing,* 60(5).

Gamblin, B., Lamontagne, P., Morniche, A., Smith, R. & Taylor, J. Year: Published. Bracken and its control in the state forests of Normandy. *Bracken'85 International Conference– Bracken. Ecology, land use and control technology*.

Gates, D. M., Keegan, H. J., Schleter, J. C. & Weidner, V. R. 1965. Spectral properties of plants. *Applied optics,* 4(1)**,** 11-20.

Ghosh, A. & Joshi, P. 2014. A comparison of selected classification algorithms for mapping bamboo patches in lower Gangetic plains using very high resolution WorldView 2 imagery. *International Journal of Applied Earth Observation and Geoinformation,* 26**,** 298-311.

Goerner, A., Gloaguen, R. & Makeschin, F. 2007. Monitoring of the Ecuadorian mountain rainforest with remote sensing. *Journal of Applied Remote Sensing,* 1(1)**,** 013527-013527-12.

Göttlicher, D., Obregón, A., Homeier, J., Rollenbeck, R., Nauss, T. & Bendix, J. 2009. Land-cover classification in the Andes of southern Ecuador using Landsat ETM+ data as a basis for SVAT modelling. *International Journal of Remote Sensing,* 30(8)**,** 1867-1886.

Harvey, K. & Hill, G. 2001. Vegetation mapping of a tropical freshwater swamp in the Northern Territory, Australia: a comparison of aerial photography, Landsat TM and SPOT satellite imagery. *International journal of remote sensing,* 22(15)**,** 2911-2925.

Hilbert, D. W. & Ostendorf, B. 2001. The utility of artificial neural networks for modelling the distribution of vegetation in past, present and future climates. *Ecological modelling,* 146(1)**,** 311-327.

Holland, J. & Aplin, P. 2013. Super-resolution image analysis as a means of monitoring bracken (Pteridium aquilinum) distributions. *ISPRS Journal of Photogrammetry and Remote sensing,* 75**,** 48-63.

Huang, C.-y. & Asner, G. P. 2009. Applications of remote sensing to alien invasive plant studies. *Sensors,* 9(6)**,** 4869-4889.

Huang, C., Davis, L. & Townshend, J. 2002. An assessment of support vector machines for land cover classification. *International Journal of remote sensing,* 23(4)**,** 725-749.

Huang, C. y. & Geiger, E. L. 2008. Climate anomalies provide opportunities for large-scale mapping of non-native plant abundance in desert grasslands. *Diversity and Distributions,* 14(5)**,** 875-884.

Hurley, M. A., Hebblewhite, M., Gaillard, J.-M., Dray, S., Taylor, K. A., Smith, W., Zager, P. & Bonenfant, C. 2014. Functional analysis of Normalized Difference Vegetation Index curves reveals overwinter mule deer survival is driven by both spring and autumn phenology. *Philosophical Transactions of the Royal Society of London B: Biological Sciences,* 369(1643)**,** 20130196.

Invasive_Species_Compendium 2005. Pteridium aquilinum (bracken) http://www.cabi.org/isc/datasheet/45596

paper for. Invasive Species Compendium

Irons, J. R., Dwyer, J. L. & Barsi, J. A. 2012. The next Landsat satellite: The Landsat data continuity mission. *Remote Sensing of Environment,* 122**,** 11-21.

Jia, K., Wei, X., Gu, X., Yao, Y., Xie, X. & Li, B. 2014. Land cover classification using Landsat 8 operational land imager data in Beijing, China. *Geocarto International,* 29(8)**,** 941-951.

Jönsson, P. & Eklundh, L. 2004. TIMESAT—a program for analyzing time-series of satellite sensor data. *Computers & Geosciences,* 30(8)**,** 833-845.

Ju, J., Kolaczyk, E. D. & Gopal, S. 2003. Gaussian mixture discriminant analysis and sub-pixel land cover characterization in remote sensing. *Remote Sensing of Environment,* 84(4)**,** 550-560.

Killick, D. J. B. 1963. An account of the plant ecology of the Cathedral Peak area of the Natal Drakensberg. *Mem. 34 Bot. Survey S. Afr.*

Knapp, A. & Carter, G. 1998. Variability in leaf optical properties among 26 species from a broad range of habitats. *American Journal of Botany,* 85(7)**,** 940-940.

Kokaly, R. F., Despain, D. G., Clark, R. N. & Livo, K. E. 2003. Mapping vegetation in Yellowstone National Park using spectral feature analysis of AVIRIS data. *Remote Sensing of Environment,* 84(3)**,** 437-456.

Laba, M., Downs, R., Smith, S., Welsh, S., Neider, C., White, S., Richmond, M., Philpot, W. & Baveye, P. 2008. Mapping invasive wetland plants in the Hudson River National Estuarine Research Reserve using quickbird satellite imagery. *Remote Sensing of Environment,* 112(1)**,** 286-300.

Li, P., Jiang, L. & Feng, Z. 2013. Cross-comparison of vegetation indices derived from Landsat-7 enhanced thematic mapper plus (ETM+) and Landsat-8 operational land imager (OLI) sensors. *Remote Sensing,* 6(1)**,** 310-329.

Lillesand, T., Kiefer, R. W. & Chipman, J. 2008. *Remote sensing and image interpretation*, John Wiley & Sons.

Linderman, M., Liu, J., Qi, J., An, L., Ouyang, Z., Yang, J. & Tan, Y. 2004. Using artificial neural networks to map the spatial distribution of understorey bamboo from remote sensing data. *International Journal of Remote Sensing,* 25(9)**,** 1685-1700.

Lowday, J. & Marrs, R. 1992. Control of bracken and the restoration of heathland. I. Control of bracken. *Journal of Applied Ecology***,** 195-203.

M.-Muslim, A., Foody, G. M. & Atkinson, P. M. 2007. Shoreline mapping from coarse-spatial resolution remote sensing imagery of Seberang Takir, Malaysia. *Journal of Coastal Research***,** 1399-1408.

Marrs, R. & Hicks, M. 1986. Study of vegetation change at Lakenheath Warren: a re-examination of AS Watt's theories of bracken dynamics in relation to succession and vegetation management. *Journal of Applied Ecology***,** 1029-1046.

McDonald, E. R., Wu, X., Caccetta, P. & Campbell, N. 2002. *Illumination correction of Landsat TM data in south east NSW*, Environment Australia.

McGlone, M. S., Wilmshurst, J. M. & Leach, H. M. 2005. An ecological and historical review of bracken (Pteridium esculentum) in New Zealand, and its cultural significance. *New Zealand Journal of Ecology***,** 165-184.

Mehltreter, K., Walker, L. R. & Sharpe, J. M. 2010. *Fern ecology*, Cambridge University Press.

Mehner, H., Cutler, M., Fairbairn, D. & Thompson, G. 2004. Remote sensing of upland vegetation: the potential of high spatial resolution satellite sensors. *Global ecology and biogeography,* 13(4)**,** 359-369.

Miller, A., Bryant, E. & Birnie, R. Year: Published. A study of land cover and land cover changes in the Northern forest of New England using Landsat MSS data. *PROCEEDINGS OF THE THEMATIC CONFERENCE ON GEOLOGIC REMOTE SENSING*. ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN, II-299.
Miller, D., Morrice, J. & Whitworth, P. 1990. Bracken distribution and spread in upland Scotland: an assessment using digital mapping techniques. *AIAS Occasional Publication,* (40)**,** 121-132.
Mushore, T. D., Mutanga, O., Odindi, J. & Dube, T. 2016. Assessing the potential of integrated Landsat 8 thermal bands, with the traditional reflective bands and derived vegetation indices in classifying urban landscapes. *Geocarto International,* (just-accepted)**,** 1-34.
Mutanga, O., Adam, E., Adjorlolo, C. & Abdel-Rahman, E. M. 2015. Evaluating the robustness of models developed from field spectral data in predicting African grass foliar nitrogen concentration using WorldView-2 image as an independent test dataset. *International Journal of Applied Earth Observation and Geoinformation,* 34**,** 178-187.
Mutanga, O., Adam, E. & Cho, M. A. 2012. High density biomass estimation for wetland vegetation using WorldView-2 imagery and random forest regression algorithm. *International Journal of Applied Earth Observation and Geoinformation,* 18**,** 399-406.
Mutanga, O. & Skidmore, A. K. 2004. Narrow band vegetation indices overcome the saturation problem in biomass estimation. *International Journal of Remote Sensing,* 25(19)**,** 3999-4014.
Myers, D. A., Vogelmann, T. C. & Bornman, J. F. 1994. Epidermal focussing and effects on light utilization in Oxalis acetosella. *Physiologia Plantarum,* 91(4)**,** 651-656.
Ngubane, Z. C. 2014. *Evaluating the Potential of WorldView-2's Strategically Located Bands in Mapping the Bracken Fern (Pteridium Aquilinum (L.) Kuhn).* University of KwaZulu-Natal, Pietermaritzburg.
O'Connor, T. 2005. Influence of land use on plant community composition and diversity in Highland Sourveld grassland in the southern Drakensberg, South Africa. *Journal of Applied Ecology,* 42(5)**,** 975-988.
Odindi, J., Adam, E., Ngubane, Z., Mutanga, O. & Slotow, R. 2014. Comparison between WorldView-2 and SPOT-5 images in mapping the bracken fern using the random forest algorithm. *Journal of Applied Remote Sensing,* 8(1)**,** 083527-083527.
Oinonen, E. 1967. The correlation between the size of Finnish bracken (Pteridium aquilinum (L.) Kuhn.) clones and certain periods of site history.
Oldham, C., Crebbin, G., Dobbs, S. & Gaynor, A. 2013. Engineers engaging community: Water and energy. *Synthesis Lectures on Engineers, Technology, and Society,* 7(2)**,** 1-116.
Page, C. 1976. The taxonomy and phytogeography of bracken—a review. *Botanical Journal of the Linnean Society,* 73(1-3)**,** 1-34.
Pahlevan, N., Lee, Z., Wei, J., Schaaf, C. B., Schott, J. R. & Berk, A. 2014. On-orbit radiometric characterization of OLI (Landsat-8) for applications in aquatic remote sensing. *Remote Sensing of Environment,* 154**,** 272-284.
Pahlevan, N. & Schott, J. R. 2013. Leveraging EO-1 to evaluate capability of new generation of Landsat sensors for coastal/inland water studies. *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of,* 6(2)**,** 360-374.
Pakeman, R. & Marrs, R. 1996. Modelling the effects of climate change on the growth of bracken (Pteridium aquilinum) in Britain. *Journal of Applied Ecology***,** 561-575.
Pakeman, R., Marrs, R., Howard, D., Barr, C. & Fuller, R. 1996. The bracken problem in Great Britain: its present extent and future changes. *Applied Geography,* 16(1)**,** 65-86.

Pakeman, R., Marrs, R. & Jacob, P. 1994. A model of bracken (Pteridium aquilinum) growth and the effects of control strategies and changing climate. *Journal of applied ecology***,** 145-154.
Pakeman, R. J. & Marrs, R. H. 1992. Vegetation development on moorland after control of Pteridium aquilinum with asulam. *Journal of Vegetation Science***,** 707-710.
Park, S. C., Park, M. K. & Kang, M. G. 2003. Super-resolution image reconstruction: a technical overview. *Signal Processing Magazine, IEEE,* 20(3)**,** 21-36.
Parks, J. C. & Werth, C. R. 1993. A study of spatial features of clones in a population of bracken fern, Pteridium aquilinum (Dennstaedtiaceae). *American Journal of Botany***,** 537-544.
Parry, M. & Cox, B. Year: Published. Technical summary. *In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by*. Citeseer.
Price, J. 1992. Variability of high-resolution crop reflectance spectra. *International Journal of Remote Sensing,* 13(14)**,** 2593-2610.
Riaño, D., Chuvieco, E., Salas, J. & Aguado, I. 2003. Assessment of different topographic corrections in Landsat-TM data for mapping vegetation types (2003). *Geoscience and Remote Sensing, IEEE Transactions on,* 41(5)**,** 1056-1061.
Roos, K., Rollenbeck, R., Peters, T., Bendix, J. & Beck, E. 2010. Growth of tropical bracken (Pteridium arachnoideum): response to weather variations and burning. *Invasive Plant Science and Management,* 3(4)**,** 402-411.
Rosen, D. Z., Lewis, C. A. & Illgner, P. M. 1999. PALAEOCLIMATIC AND ARCHAEOLOGICAL IMPLICATIONS OF ORGANIC-RICH SEDIMENTS AT TIFFTIDELL SKI RESORT, NEAR RHODES, EASTERN CAPE PROVINCE, SOUTH AFRICA. *Transactions of the Royal Society of South Africa,* 54(2)**,** 311-321.
Roy Chowdhury, R. & Schneider, L. C. 2004. *Land-cover/use in the southern Yucatán peninsular region, Mexico: classification and change analysis*, Integrated land-change science and tropical deforestation in the southern Yucatán: final frontiers. Clarendon, Oxford, UK.
Schmook, B., Palmer Dickson, R., Sangermano, F., Vadjunec, J. M., Eastman, J. R. & Rogan, J. 2011a. A step-wise land-cover classification of the tropical forests of the Southern Yucatan, Mexico. *International Journal of Remote Sensing,* 32(4)**,** 1139-1164.
Schmook, B., Palmer Dickson, R., Sangermano, F., Vadjunec, J. M., Eastman, J. R. & Rogan, J. 2011b. A step-wise land-cover classification of the tropical forests of the Southern Yucatán, Mexico. *International Journal of Remote Sensing,* 32(4)**,** 1139-1164.
Schneider, L. & Geoghegan, J. 2006. Land abandonment in an agricultural frontier after a plant invasion: the case of bracken fern in southern Yucatán, Mexico. *Agricultural and Resource Economics Review,* 35(1)**,** 167.
Schneider, L. C. & Fernando, D. N. 2010. An untidy cover: invasion of bracken fern in the shifting cultivation systems of Southern Yucatán, Mexico. *Biotropica,* 42(1)**,** 41-48.
Schuster, C., Förster, M. & Kleinschmit, B. 2012. Testing the red edge channel for improving land-use classifications based on high-resolution multi-spectral satellite data. *International Journal of Remote Sensing,* 33(17)**,** 5583-5599.
Sheffield, E., Wolf, P. G. & Haufler, C. 1989. How big is a bracken plant? *Weed Research,* 29(6)**,** 455-460.
Shoko, C., Clark, D., Mengistu, M., Bulcock, H. & Dube, T. 2015a. Estimating spatial variations of total evaporation using multispectral sensors within the uMngeni catchment, South Africa. *Geocarto International***,** 1-22.

Shoko, C., Clark, D., Mengistu, M., Dube, T. & Bulcock, H. 2015b. Effect of spatial resolution on remote sensing estimation of total evaporation in the uMngeni catchment, South Africa. *Journal of Applied Remote Sensing,* 9(1)**,** 095997-095997.
Sibanda, M., Mutanga, O., Rouget, M. & Odindi, J. 2015. Exploring the potential of in situ hyperspectral data and multivariate techniques in discriminating different fertilizer treatments in grasslands. *Journal of Applied Remote Sensing,* 9(1)**,** 096033-096033.
Singh, K., Forbes, A. & Akombelwa, M. 2014. The Evaluation of High Resolution Aerial Imagery for Monitoring of Bracken Fern. *South African Journal of Geomatics,* 2(4)**,** 296-208.
Sohn, Y. & Rebello, N. S. 2002. Supervised and unsupervised spectral angle classifiers. *Photogrammetric Engineering and Remote Sensing,* 68(12)**,** 1271-1282.
Souza, A., Galvao, L. & Santos, J. 2010. Relationships between Hyperion-derived vegetation indices, biophysical parameters, and elevation data in a Brazilian savannah environment. *Remote Sensing Letters,* 1(1)**,** 55-64.
Stathakis, D., Perakis, K. & Savin, I. 2012. Efficient segmentation of urban areas by the VIBI. *International journal of remote sensing,* 33(20)**,** 6361-6377.
Su, L., Chopping, M. J., Rango, A., Martonchik, J. V. & Peters, D. P. 2007. Support vector machines for recognition of semi-arid vegetation types using MISR multi-angle imagery. *Remote Sensing of Environment,* 107(1)**,** 299-311.
Suazo, I. 1998. Aspectos ecologicos de la especie invasora Pteridium aquilinum (L.) Kuhn en una selva humeda de la region de Chajul. *Chiapas, Mexico. Facultad de Biologia. Morelia, Michoacan, Universidad Michoacana de San Nicolas de Hidalgo,* 114.
Sycholt, A. 2002. *A Guide to the Drakensberg*, Struik.
Taylor, J. 1986. The bracken problem: a local hazard and global issue. *Bracken: Ecology, Land use and Control Technology. Parthenon Publishing. Carnforth*.
Taylor, J. 1990a. The bracken problem: a global perspective. *AIAS Occasional Publication,* (40)**,** 3-19.
Taylor, J. E. 1990b. *Feasibility of remote sensing for monitoring bracken fern in eastern Australia*.
Taylor, J. E. 1993. Factors causing variation in reflectance measurements from bracken in eastern Australia. *Remote Sensing of Environment,* 43(2)**,** 217-229.
Thenkabail, P. S., Smith, R. B. & De Pauw, E. 2000. Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. *Remote sensing of Environment,* 71(2)**,** 158-182.
Tong, C., Le Duc, M., Ghorbani, J. & Marrs, R. 2006. Linking restoration to the wider landscape: A study of a bracken control experiment within a upland moorland landscape mosaic in the Peak District, UK. *Landscape and Urban Planning,* 78(1)**,** 115-134.
Turner, B. L., Geoghegan, J., Lawrence, D., Radel, C., Schmook, B., Vance, C., Manson, S., Keys, E., Foster, D. & Klepeis, P. 2016. Land system science and the social–environmental system: the case of Southern Yucatán Peninsular Region (SYPR) project. *Current Opinion in Environmental Sustainability,* 19**,** 18-29.
Ustin, S. L. & Gamon, J. A. 2010. Remote sensing of plant functional types. *New Phytologist,* 186(4)**,** 795-816.
Van Der Meer, F. & de Jong, S. M. 2001. *Imaging Spectrometry:: Basic Principles and Prospective Applications*, Springer Science & Business Media.
Vetter, J. 2009. A biological hazard of our age: Bracken fern [Pteridium aquilinum (L.) Kuhn]—A review. *Acta Veterinaria Hungarica,* 57(1)**,** 183-196.
Vogelmann, T. & Martin, G. 1993. The functional significance of palisade tissue: penetration of directional versus diffuse light. *Plant, Cell & Environment,* 16(1)**,** 65-72.

Wessman, C. A., Bateson, C. A. & Benning, T. L. 1997. Detecting fire and grazing patterns in tallgrass prairie using spectral mixture analysis. *Ecological Applications,* 7(2)**,** 493-511.

Wild-Flowers 2014. http://wildflowerfinder.org.uk/.

Williams, C. 2011. *Medicinal Plants in Australia Volume 2: Gums, Resins, Tannin and Essential Oils*, Rosenberg Publishing.

Wolf, P. G., Haufler, C. H. & Sheffield, E. 1987. Electrophoretic evidence for genetic diploidy in the bracken fern (Pteridium aquilinum). *Science,* 236(4804)**,** 947-949.

Wulder, M. A. & Franklin, S. E. 2003. Remote Sensing of forest environments, Introduction. *Remote Sensing of Forest Environments.* Springer.

Xie, Y., Sha, Z. & Yu, M. 2008. Remote sensing imagery in vegetation mapping: a review. *Journal of plant ecology,* 1(1)**,** 9-23.

Xu, M., Watanachaturaporn, P., Varshney, P. K. & Arora, M. K. 2005. Decision tree regression for soft classification of remote sensing data. *Remote Sensing of Environment,* 97(3)**,** 322-336.

Yu, X., Guo, X. & Wu, Z. 2014. Land surface temperature retrieval from Landsat 8 TIRS—Comparison between radiative transfer equation-based method, split window algorithm and single channel method. *Remote Sensing,* 6(10)**,** 9829-9852.