Parthenium hysterophorus distribution and Efficacy of Control in Hluhluwe-Imfolozi Park, Northern KwaZulu-Natal

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PREFACE

The research contained in this thesis was completed by the candidate while based in the School of Life Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by Ezemvelo KZN Wildlife (EKZNW) and the JB Marks Education Trust Fund.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by candidate.

[redacted]

Sethabile Khwezi Mbatha

November 2020

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

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Dr. Michelle Tedder	Dr. Clinton Carbutt	Prof. Onisimo Mutanga
November 2020	November 2020	November 2020

DECLARATION: PLAGIARISM

I, Sethabile Mbatha, declare that:

1) The research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;
2) This dissertation has not been submitted in full or in part for any degree or examination to any other university;
3) This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;
4) This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

   a) their words have been re-written but the general information attributed to them has been referenced;

   b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;
5) Where I have used material for which publications followed, I have indicated in detail my role in the work;
6) This dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;
7) This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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ABSTRACT

Throughout history, the effective control of biological invasions has been challenging, consequently, requiring viable techniques to manage their spread while not influencing biological threats to health, crops and livestock (pestilence, weeds, locusts, wild animals etc.) with not much concern, in comparison, to the natural environment. Invasive weeds are plant species that are effectively encroaching in geographic regions where they do not naturally occur. They imperil the presence of indigenous species in an environment and are one of, amongst many, the primary drivers of vegetation change. Natural, social, and monetary components are both directly and indirectly influenced by the spread of invasive alien plants. Published literature shows a wide range of the negative influences presented by invasive weeds on biodiversity and plant communities. However, it does not show the immediate and short to medium term impacts of current management strategies. This study, therefore, aimed to (1) spatially detect *Parthenium hysterophorus* infestation levels in a 10 km buffer zone of the Hluhluwe-Imfolozi Park protected area and (2) evaluate the short and short to medium term efficacy of the current management strategies used by Ezemvelo KZN Wildlife (EKZNW) and their impact on non-target plant communities. *Parthenium hysterophorus,* commonly known as the Famine weed, is an alien invasive plant of global significance, being noted amongst the top seven problematic weeds globally. Since the *P. hysterophorus* outbreak in the KwaZulu-Natal province, EKZNW has played a significant role in controlling *P. hysterophorus* invasions. However, higher *P. hysterophorus* infestation levels observed outside EKZNW protected areas has led to this study making use of a one-class support vector machine algorithm and Sentinel-2 MSI imagery to detect *P. hysterophorus* extent of encroachment. Considering the ecological integrity of protected areas, buffer zone management is important to reduce biotic stress on neighbouring communities. The one-class support vector machine algorithm was implemented on Google Earth Engine (GEE) and a classification accuracy of 81.97% was obtained from using Sentinel-2 spectral bands and computed vegetation indices. *Parthenium hysterophorus* extent of encroachment was 129,545325 km^2 within the area of study, compared to a lower 119,89133 km^2 establishment of other indigenous species. More than 50% of the study area is encroached which requires urgent attention. Evaluating the short to medium term effectiveness of metsulfuron-methyl 600g kg^{-1} (FORESTER), a registered herbicide used to control *P. hysterophorus* in EKZNW protected areas, the herbicide was applied in plots both inside and outside the protected area and *P. hysterophorus* mortality rates were monitored over time. In this study, the metsulfuron-methyl 600g kg^{-1} herbicide proved to be effective in controlling *P. hysterophorus*. Overall, the study informs management of the threat EKZNW is

facing to achieve a *P. hysterophorus* free buffer zone and motivates for continued use of the metsulfuron-methyl 600g kg-1 herbicide in controlling *P. hysterophorus* as it effectively kills the weed and does not influence non-targeted vegetation.

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LIST OF ABBREVIATIONS

AVHRR	Advanced Very High-Resolution Radiometer
CARA	Conservation of Agricultural Resources Act
CBD	Convention on Biological Diversity
CBD	Central Business District
DAT	Days after treatment
DEFF	Department of Environment, Forestry, and Fisheries
DOS	Dark-object observation
DVI	Difference Vegetation Index
EKZNW	Ezemvelo KZN Wildlife
EM	Electromagnetic spectrum
EPWP	Expanded Public Works Programme
EROS	Earth Resources Observation and Science
ESA	European Space Agency
EVI	Enhanced Vegetation Index
G Chl Index	Green Chlorophyll Index
GDVI	Green Difference Vegetation Index
GEE	Google Earth Engine
GI	Greenness Index
GIS	Geographic Information System

GISD	Global Invasive Species Database
GNDVI	Green Normalized Difference Vegetation Index
GPS	Global Positioning System
GRVI	Green Ratio Vegetation Index
HiP	Hluhluwe-Imfolozi Park
IAP	Invasive Alien Plant
IAS	Invasive Alien Species
IASP	Invasive Alien Species Program
IPCC	International Plant Protection Convention
IPVI	Infrared Percentage Vegetation Index
ISC	Invasive Species Compendium
IUCN	International Union for Conservation of Nature
IWM	Integrated weed management
LC1	Level 1C
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Maputaland-Pondoland-Albany
MSI	Multispectral Instrument
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NEMBA	National Environmental Management: Biodiversity Act

NIR	Near infrared
OA	Overall accuracy
OCC	One-Class Classification
OCSVM	One-Class Support Vector Machine
PA	Producer’s accuracy
POI	Polygons of Interest
SAPIA	Southern African Plant Invaders Atlas
SAVI	Soil Adjusted Vegetation Index
SRI	Simple Ratio Index
SWIR	Short-wave infrared
TOA	Top of atmosphere
UA	User’s accuracy
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VI	Vegetation Index

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CHAPTER 1

Introduction

1.1 Study rationale

The apparent advancement of invasive alien species is acknowledged as a global threat to natural ecosystems (Vitousek et al., 1996, Bradley, 2010, Somodi et al., 2012). Although globalization has brought many benefits to humans at large, it has also been accompanied by many challenges, including alien invasions. Many biogeographic barriers are breached during globalization causing many native species to be exposed to environments that are modified by invasive plant and animal species (Richardson et al., 2005). Biological invasion rates have escalated and their consequences have increased significantly in recent years (Kohli et al., 2004; Reaser et al., 2008). South Africa has high biological diversity that is threatened by alien species invasions (Cadman et al., 2010). This biological diversity includes more than 18 000 vascular plant species, of which 80% cannot be found anywhere else in the world. South Africa is also native to many species of mammals, birds, and insects. However, over the years the country's unique biological diversity has been threatened by invasive alien species, notably plants. The government enacted the invasive alien plant control management plan in 2014 which requires that any proposed control measures must be evaluated on effectiveness in controlling the target species and their impact on the non-target native species. This study presents the detected spread of *Parthenium hysterophorus* and its management in buffer and protected areas of Ezemvelo KwaZulu-Natal Wildlife in Northern KwaZulu-Natal, South Africa. The KwaZulu-Natal province has experienced high levels of *P. hysterophorus* encroachment since it first appeared in Inanda in 1880 (McConnachie et al., 2011). A governmental organization, Ezemvelo KZN Wildlife (EKZNW) is championing the management of invasive species to mitigate environmental risks and ecological meagerness in KwaZulu Natal in compliance with the National Environmental Management: Biodiversity Act of 2004 and the requisites under Section 75(4) for category 1b invader species. In South Africa, there are four Acts that apply to alien invasive plants. They are:

- National Environmental Management: Biodiversity Act 10 of 2004 (NEMBA): *Parthenium* is a Category lb species requiring compulsory control and a management plan. Regulated by the Department of Environment, Forestry, and Fisheries (DEFF)

- The Conservation of Agricultural Resource Act 43 of 1983 (CARA): *Parthenium* is a Category 1 plant: declared weed (not allowed to occur on any land). Regulated by DALRRD
- Fertilizers, Farm Feeds, Agricultural Remedies and Stock Remedies Act 36 of 1947: Forester (metsulfuron methyl 600g kg-1) is a registered herbicide (L8891) for the control of *Parthenium* in rangelands. Regulated by the office of the Registrar of Act 36, DALRRD. Forester TM is a wettable powder herbicide for the control and eradication of certain woody invaders and noxious plants in forestry areas, natural pastures and conservation areas.

- Agricultural Pest Act 36 of 1983: Provide for measures by which agricultural pests may be prevented and combated and includes pathogens, invertebrates, vertebrates, and mediums/substances which might be sources of infection

EKZNW uses chemical control to manage *P. hysterophorus*, amongst other weed species, in the KwaZulu-Natal province. This study used remotely sensed information to establish the threat of the weed within the target area and evaluated the effectiveness of the chemical control method used by the organization over a short- and short-medium term period. The information and knowledge generated in this study will potentially contribute towards devising effective *P. hysterophorus* management strategies to maintain the ecological integrity of protected areas in the face of alien plant invasions.

1.2 Justification

The invasive *P. hysterophorus* may be successfully controlled by biological and chemical control strategies (Strathie et al., 2011). Chemical control methods have been widely used to control infestations along roadsides and in agricultural fields as they are successful and relatively low-cost (Goodall et al., 2010). However, the effectiveness of herbicides in controlling *P. hysterophorus* is variable under different conditions. For example, the use of herbicides alone in some instances has been shown to be ineffective in suppressing the germination of *P. hysterophorus* seeds in the soil (Goodall et al., 2010). Ineffective control of potential germination by the seeds enhances the chances of *P. hysterophorus* resurgence. So, it is important to evaluate the efficacy of the herbicides under well-defined environmental conditions to formulate appropriate *P. hysterophorus* management strategies. There is ongoing implementation of control strategies to manage *P. hysterophorus* in South Africa with a critical goal of establishing a national invasive alien control programme. More precisely, Section 75(4) of NEM:BA (Act 10 of 2004) calls for the creation of a National *Parthenium* Programme which will come into effect in April 2021 when the National *Parthenium* Strategy and the National *Parthenium* Implementation Plan are signed into effect under the auspices of DEFF. The extent of encroachment that can be spatially represented must be determined before implementation to formulate appropriate control strategies. Terblanche et al., (2016) suggested that close monitoring is essential to adequately control the spread of *P. hysterophorus*. The impact of *P. hysterophorus* on biodiversity has been recorded in other countries, but not in South Africa. There is a need to monitor the distribution and spread of *P. hysterophorus* in South Africa, its impact on biodiversity of native species and evaluate the efficacy of proposed control strategies to formulate a *P. hysterophorus* management plan suitable for South Africa.

1.3 Research Questions Per Chapter

1.3.1 Chapter Three: Spatial Gradient of *Parthenium* Infestation

1.3.1.1 What are the actual encroachment levels of *P. hysterophorus* outside of Hluhluwe-Imfolozi Park?

1.3.1.2 What is the capability of the freely available, Sentinel 2 Multispectral Instrument (MSI) remote sensing imagery to determine the spatial distribution of *P. hysterophorus* with the use of a singular class classification method (one-class support vector machine)?

1.3.1.3 What is the distribution of *P. hysterophorus* as detected using spectral bands, vegetation indices (VIs), and the combination of spectral bands and VIs within the study area?

1.3.2 Chapter Four: *Parthenium* Control

1.3.2.1 Are the known management strategies, such as the use of herbicide, effective in controlling the above-ground parts of *P. hysterophorus*, 14 days after treatment and 12 months after control?

1.3.2.2 How do chemical herbicides used to control *P. hysterophorus* affect non-target plant species diversity in Ezemvelo KZN Wildlife protected areas?

1.4 Problem Statement

Demand for the collaboration of experts in remote sensing and plant ecologists is undeniable because of the existing gap in literature. As stated in the literature, accurate maps are of individual plant species (Kushwasha, 2012), however, when Ismail et al., (2016) reviewed the use of remote sensing data when mapping invasive species, studies on individual organisms were noted to be very rare. This, therefore, confirms the lack of IAP (object-based) spatial distribution maps, which, prompts future research in ecological remote sensing. While interested in mapping the distribution of a specific invasive alien plant, ecologists also have acknowledged the need to assess the feasibility of current management strategies.

1.5 Aim

The main aim of the present study was to spatially evaluate *Parthenium hysterophorus* infestation levels and the efficacy of current management strategies used by Ezemvelo KZN Wildlife and their impact on non-target coexisting plant species within the study area.

1.6 Objectives

The objectives of this study were to:

1. Spatially map and determine the levels of encroachment of *P. hysterophorus* within a 10 km buffer zone of the northern boundary of Hluhluwe-Imfolozi Park in the KwaZulu Natal province of South Africa.
2. Test the short to medium term efficacy of chemical herbicides in controlling *P. hysterophorus* and their impact on other non-target plant species in invaded areas.

1.7 Thesis structure

The first chapter (Chapter 1) of this dissertation gives a general introduction to the presented study. Chapter 1 unpacks the nature of the study and clarifies its significance. The second chapter (Chapter 2) evaluates peer-reviewed methods and provides opportunities for contextualising the objectives of the presented study. The following third and fourth chapters are experimental chapters with each one reporting a distinct research objective. Chapter 3 focuses on the use of remote sensing applications, specifically, a singular-classification algorithm, to spatially represent the degree of infestation by the target species within the study area. After defining *P. hysterophorus* extent of encroachment in chapter 3, chapter 4 evaluates the current management strategies being implemented by Ezemvelo KZN Wildlife to achieve a *P. hysterophorus* free environment. From an ecological perspective, chapter 4 also investigates the influence of chemicals used to control *P. hysterophorus* on non-targeted flora. The final chapter, chapter 5, integrates the work, provides conclusions, recommendations, and research possibilities for future studies.

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CHAPTER 2

Spatial Detection and Management of Invasive Alien Plants: A review

2.1 Abstract

Invasive alien species are establishing and expanding in growing numbers in many parts of the world, and these invasions are often followed by major negative effects on ecosystems, the environment, and human health. The factors influencing the spread of invasive alien species across broad regions of South Africa and their consequential impacts have been broadly identified. In South Africa, an estimated annual cost of R6.5 billion is needed to curb the spread of biological invasions, and if they are left unmanaged, the total effect on ecosystem resources will likely increase by an order of magnitude. Nevertheless, there are still inadequate practical methods for managing plant invasions and if the negative effects of invasive alien species are to be avoided, there is a need for organized strategic management. Here we review the ecological complexity of mapping invasive alien species and suggest ecologically sound remote sensing approaches in detecting invasive alien plants when producing low-cost and accurate maps. Mapping the spread of invasive alien species is important to inform strategic management approaches. The review also taps into understanding the response of the natural ecosystem to invasive alien species and the implementation of present-day management strategies. Remote sensing applications are useful in spatially detecting and mapping invasive alien plants when the target species has distinct physical, phylogenetic, and phenological features from the invaded plant community. Robust multispectral sensors have proved to be most significant in identifying weeds for low-cost mapping. This review proposes the early implementation of adequate management strategies for controlling plant invasions to save costs. It is also necessary to evaluate the effectiveness and the response of the natural environment of the control strategies being implemented.

2.2 Introduction

According to the International Union for Conservation of Nature (IUCN), invasive species are defined as introduced non-indigenous organisms occurring in ecosystems where they have competitive characteristics allowing them to dominate (Poona, 2008). The introduction of foreign plant species in South Africa began in the 1600s and introductions accelerated during the 1800s (Moran et al., 2013). More specifically, foreign plants were first recognized as a problem in 1906 when the South African parliament met to address the problem created by

Opuntia ficus-indica infestation (Moran et al., 2013). Since then, the impact of invasive alien species (IAPs) on South Africa's indigenous flora has been increasing persistently (Poona, 2008). Overarching natural dispersal mechanisms of IAPs and anthropogenic travel around the world are the leading causes of accelerated introductions (Richardson et al., 2005 and Weber et al., 2008).

The introduction of exotic species can be intentional, such as plants introduced for food supply, or unintentional, through either tourism, trade, and travel which may accidentally disperse non-indigenous plant species by, for example, conveying plant seeds that may spread and persist until the species attains a self-sustaining population (McNeely, 2001b). As a result, the movement of the IUCN towards conservation is significantly challenged (McNeely, 2001a). The National Environmental Management: Biodiversity Act (NEMBA) (10/2004) released a draft with laws and regulations on alien and invasive species in 2009. The draft outlines species categories which are listed according to the extent of the threat the species poses to the natural environment. Category 1a comprises of species that need to be urgently eradicated and category 1b are species that require the implementation of control measures. In category 2, there are species that may be cultivated only by individuals who own a permit and must monitor spread. Category 4 contains a list of species that have only been exempted to occur in certain geographic areas. *P. hysterophorus* is a category 1b invader, requiring compulsory control and a management plan. Despite the enactment of the NEMBA act, South Africa has failed to successfully eradicate problematic species (Wilson et al 2013). The major reason for this has been attributed to the improper application of chemicals, farmers' lack of participation, insufficient ecological knowledge and low herbicidal efficacy (Wilson et al., 2013). In addition, South Africa is ultimately challenged by the lack of provisional funds and regular assessment and monitoring of implemented control projects for the NEMBA listed taxa (Wilson et al, 2013). By 2010, the Southern African Plant Invaders Atlas (SAPIA) database reported an invasion of 660 flora species in South Africa, and, about 8750 non-native taxa. Of the mentioned invasive taxa, only 64 have been acknowledged to be efficiently controlled in South Africa (Wilson et al., 2013). An annual cost of R6.5 billion is needed to curb the spread of biological invasions in South Africa (Wilson et al., 2013). This greatly impacts the countries' economic growth as additional funds are required in scenarios where infestations are not managed, therefore, increasingly threatening biodiversity and human health (Wilson et al., 2013). Efforts to manage troublesome species may include the deliberate importation of the weed's natural enemies from the weed's indigenous home as biocontrol agents, causing death to weeds (Royimani et al., 2019). Other deliberate anthropogenic introductions are attributed to economic interests, for instance, acquiring exotic plants for ornamental use, consumption, shelter, medicinal use, and/or afforestation (Kunwar, 2003 and McNeely, 2001b).

Poona (2008) identified *Lantana camara* and *Jacaranda mimosifolia* as IAPs, amongst others, being initially valued by humans as ornamental plants in South Africa. Nevertheless, documented negative impacts of exotic flora on human health and ecosystem functioning outweighs the importance of intentional or rather economically influenced introductions (Poona, 2008). For example, *Parthenium hysterophorus* (famine weed) is a well-known non-indigenous plant responsible for causing human health problems such as dermatitis and asthma (Poona, 2008). Therefore, since anthropogenic invasions are presumably expected to persist (Poona, 2008), the spread of AIPs remains a crucial problem.

The factors influencing the spread of IAPs across broad regions of South Africa and their consequential impacts on the natural environment, human health, and the economy have been broadly identified. Nevertheless, there are still inadequate practical methods for managing plant invasions (Richardson and Van Wilgen, 2004). The present study reviews the ecological complexity of mapping IAPs and suggests ecologically sound remote sensing approaches in detecting IAPs to produce low-cost and accurate maps in KwaZulu-Natal. According to Niphadkar and Nagendra (2016), ecologists consult remote sensing experts to acquire information on plant and animal distributions relevant for ecological research and mapping. This study will, therefore, discuss the mapping of IAPs for invasion ecologists. Furthermore, the study evaluates the ecological interactions of IAPs in threatened ecosystems and explores present-day developments in managing biological invasions. There is a need to understand the correlation between the response of the natural ecosystem to IAPs and the implementation of present-day management strategies. This will potentially suggest a way forward for future research.

2.3 Spatial distribution of invasive alien plants

Understanding the geographic locality of foreign plant species has become important due to the sensitivity of natural ecosystems. The overall aim of examining spatial patterns of alien plant distribution is to determine the historical rates of introduction, identify the significant factors influencing large scale invasion, and the potential impact on natural communities. There is a general lack of documentation on species distributions for both indigenous and introduced species (Dark, 2004 and Gallo and Waitt, 2011). Adopting early detection approaches to mapping the spread of invasive alien plants encourages the implementation of well-informed weed management programs (Kganyago et al., 2017). Ecological conservationists need accessible and user-friendly spatial information of biological invasions for making informed decisions, and devising appropriate management approaches (Gallo and Waitt, 2011). With the increasing use of Geographic Information Systems (GIS) and Remote Sensing applications, contemporary research in ecological science is becoming more advanced (Huang and Asner, 2009, Joshi et al., 2004 and Kimothi and Dasari, 2010). However, producing spatial distribution maps of invasive alien plant species at global scales remains a challenge (Dark, 2004). Due to the difficulties of manually obtaining biogeographical and spatially referenced information on a large scale, there is a noted insufficient availability of data (Dark, 2004). As a result, studies rely on herbarium records to provide plant species distribution data (Bradley, 2014). Traditional research methods for acquiring distribution maps of alien invasive species cover entailed the manual, labour-intensive collection of field data and given that some areas have accessibility issues their application is limited (Masocha and Skidmore, 2011). More localized areas of study provide an intelligible arrangement of plant organisms on the earth's surface (Dark, 2004).

Climate change is also influencing the spatial distribution of invasive alien plants (Huang and Asner, 2009). Factors such as rainfall patterns, temperature, and nitrogen or carbon dioxide concentrations in the atmosphere are important drivers of invasion by alien species (Huang and Asner, 2009). Several studies have revealed the strong relationship between rainfall patterns and invasive alien plants (Royimani et al., 2019, Walther et al., 2009, Heller et al., 2008). Royimani et al., (2019) found that there exists a positive relationship between the spread of *Parthenium hysterophorus* and the amount of rainfall received in the invaded area. Dhileephan (2012) further explained that the production of *P. hysterophorus* seeds significantly increased following rainfall occurrences, which increased weed coverage and the negative impact on the entire ecosystem (Dhileephan, 2012). Records of global temperature reveal the severity of a warming world (Botkin et al., 2007). Due to an increased number of warmer regions, invasive alien plants are now occupying geographic areas which they previously could not inhabit (Walther et al., 2009). Also, biological invasions have been linked to increases in atmospheric carbon dioxide and nitrogen concentrations (Ziska and George, 2004, Bradford et al., 2007; Song et al., 2009). Thuiller et al. (2005) asserted that the comprehension of important climatic variables that facilitate biological invasions potentially provides early warning data, allowing for effective management strategies. Tuberlin et al., (2017) spatially represented Africa and Central Asia as the most critical areas for integrating control management plans and informing scientific research (Figure 2.1). The success of alien plant invasions should be monitored to understand the extent of expansion for mitigation or prevention measures in the future.

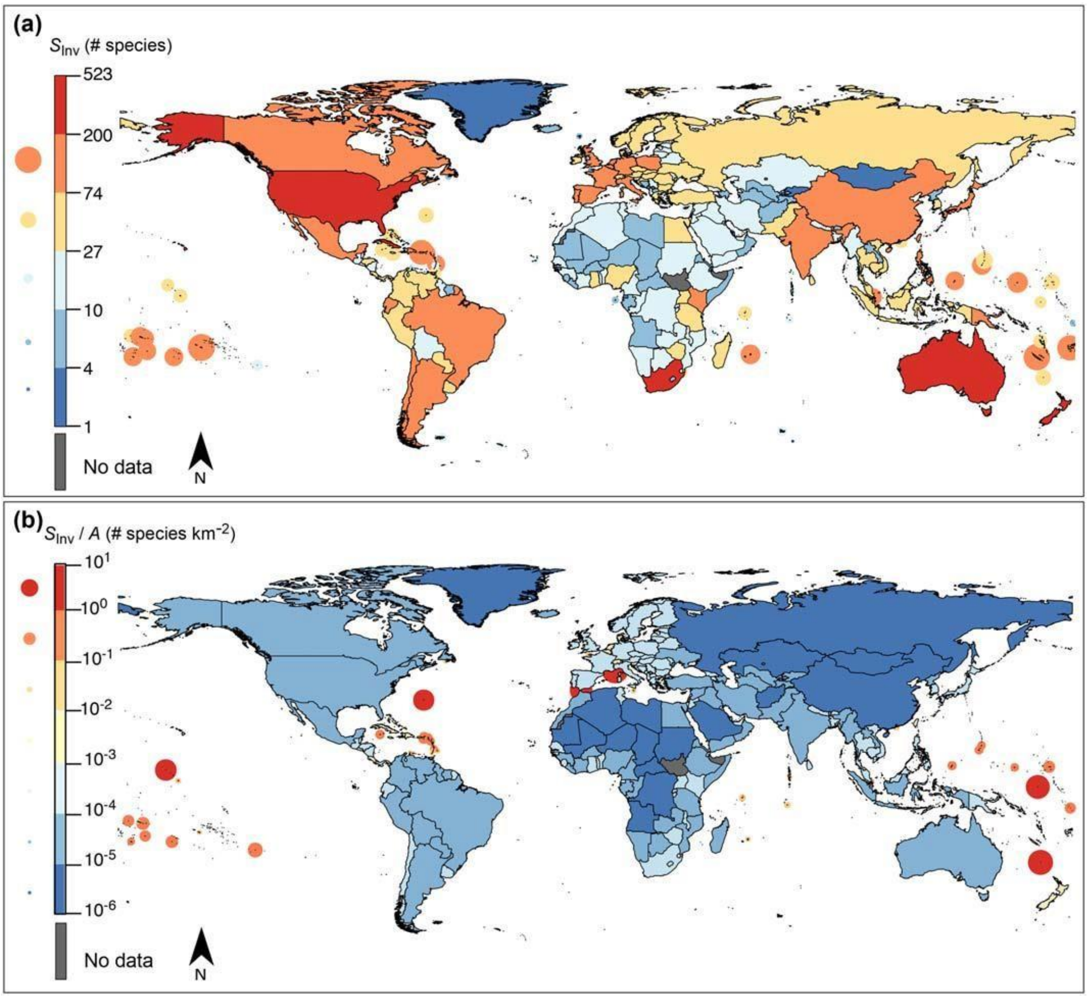

Figure 2.1: World map representing a total recording of invasive alien species in each country using collected data from the CABI Invasive Species Compendium (CABI ISC) and the Global Invasive Species Database (GISD). (a) the total number of invasive alien species recorded in the different regions and (b) displays computed values of invasive alien species, divided by the country's surface area in km^2.

2.4 Spatial detection and mapping of invasive alien plants in KwaZulu-Natal

Research suggests considerable efforts in documenting the use of remote sensing data in mapping invasion ecology (Niphadkar and Nagendra, 2016). More than a hundred publications in mapping plant invasions with the use of remote sensing technologies have appeared in the literature over the last ten years (Kushwaha, 2012). Even so, up till now, ecological scientists still have not exhaustively kept themselves up to date with making use of remote sensing technologies for mapping IAPs (Niphadkar and Nagendra, 2016). The continuous and alarming spread of invasive plants requires spatial analysis techniques to detect early infestations or determine the likelihood of invasion in order to make appropriate IAP management decisions (Bradley, 2014, Kushwaha, 2012 and Kopeć et al., 2019). Remote sensing has evolved from the initial use of aerial photographs and imagery to contemporary advancements of computational satellite measurements offered by both privately and publicly owned satellite sensors. This has enabled higher capability in temporal, spectral and spatial mapping of plant invasions (Bradley, 2014). The distinctiveness of remote sensing data acquired for a particular study amounts to its temporal resolution (revisit time), spectral resolution (total number and range of used visible and infrared bands of the electromagnetic spectrum), spatial resolution (magnitude at each pixel), and spatial extent (magnitude of the image acquired). Increased spectral resolution in the visible and infrared spectral bands of remotely acquired imagery ensures adequate distinctions of plant pigments and their chemical constituents (Bradley, 2014). Hyperspectral datasets, frequently employed in mapping IAPs have countless advanced spectral bands in the visible, shortwave and near-infrared regions that improve IAP spectral differentiation and detection (Bradley, 2014 and Peerbhay et al., 2016). However, acquiring hyperspectral datasets is expensive and the datasets also have restricted spatial and temporal extents (Bradley, 2014). Remote sensing imagery with substantial spatial extents and a very fine spatial resolution allows for improved representation of plants occurring as weeds (Bradley, 2014 and Kimothi and Dasari, 2010). However, finer spatial resolution data are mostly limited to the mapping of homogenous weed patches (Bradley, 2014). Different satellite sensors produce either fine, medium or coarse spatial resolution datasets. For example, satellite sensors with a fine spatial resolution are the Worldview-2 (WV 2), Sentinel 2 Multi-Spectral Instrument (MSI) (Lantzanakis et al., 2017), QuickBird, and IKONOS, and satellite sensors with an average spatial resolution include SPOT, Landsat and ASTER multispectral sensors and lastly, coarse spatial resolution datasets are the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High-Resolution Radiometer (AVHRR) (Bradley, 2014).

No single satellite sensor can combine maximal temporal, spectral and spatial properties throughout a substantial spatial scale, therefore limiting the selection of an appropriate remote sensing approach when mapping IAPs (Bradley, 2014). Nonetheless, Peerbhay et al., (2016) noted that the spectral signatures of IAPs reflected information to be most significant in identifying weeds remotely. Bradley (2014) suggested an overarching approach when mapping IAPs with remotely sensed data to circumvent the high cost of obtaining hyperspectral datasets. Alternatively, robust multispectral sensors can be used (Bradley, 2014 and Peerbhay et al., 2016), especially in developing countries (Royimani et al., 2019). However, the physical, phylogenetic and phenological features of the invasive weed are of significance when conducting a multispectral analysis. The target species must have distinct physical, phylogenetic and phenological features from the invaded plant community (Bradley, 2014). Also, Peerbhay et al., (2016) emphasised the observation of IAP monotypic stands when using multispectral remote sensing.

On the other hand, several studies have taken advantage of specific plant traits such as texture and phenology (Bradley, 2014) and also, not excluding structural and/or physiological traits (Niphadkar and Nagendra, 2016) in mapping invasive alien plants. Even though remotely detecting a specific plant species is challenging, distinctive phenological, textural, and spectral signatures are very helpful in making distinctions from indigenous species (Bradley, 2014). Detection techniques are more accurate for large encroachment patches, with a pixel size similar to the sensor's spatial resolution (Bradley, 2014). Determining the exact extent of encroachment patch size of a target species depends on the distinctiveness of the IAP in invaded regions (Bradley, 2014 and Peerbhay et al., 2016). With the use of the Landsat multispectral sensor, for example, detecting an invasive alien plant requires a pixel coverage of 900 m^2 whereas if using aerial photos and imagery, invasive tree species can be detected at a 4 m^2 pixel coverage (Bradley, 2014). Eventually, invasive weeds tend to dominate natural communities, therefore allowing for indigenous flora exploitation of phenological plant traits for IAP remote detection (Bradley, 2014 and Niphadkar and Nagendra, 2016). Large encroachment patches and seasonal plant phenological traits of invasive weeds have cooperatively improved the use of remote sensing technologies for studies aiming to spatially detect and map biological invasions (Bradley, 2014).

Like any other scientific method or approach, remote sensing applications in spatially detecting and mapping IAPs have limitations. Peerbhay et al., (2016) mentioned, for example, the complexity of running an analysis of remotely sensed data as it requires high computing power and specialised equipment. Secondly, even though most sensors with a moderate spatial and spectral resolution are readily accessible, they are incapable of exhaustively representing IAPs spatially. Thirdly, spatially detecting understorey species is very challenging, especially if the target weed has indistinct phenological variations, or if the canopy plants are not deciduous. Lastly, the use of very high spatial information on a broad scale is hard to achieve, due to the challenges mentioned above, therefore, negatively influencing the whole map output (Peerbhay et al., 2016).

2.5 Effects of biological invasions and ecosystem vulnerability

In 1952 and 1992, the global effects of biotic invasions were reported by the International Plant Protection Convention (IPCC) and the Convention on Biological Diversity (CBD) (Dehen-Schmutz, 2018). Van Wilgen and De Lange (2011) highlighted the lack of knowledge in understanding the exacerbating influence of IAPs on our natural ecosystems, including South Africa. The general introduction procedure of IAPs into indigenous ecosystems incorporates the initial arrival of the weed, its establishment and its subsequent spread until it becomes a notable invader (Kimothi and Dasari, 2010). In this case, the main initiator of biological diversity loss, ecosystem disturbance, and vulnerability for alien plant invasions is their spread (Poona, 2008). Thereafter, the extensive colonization by these non-indigenous species will impact differently on the newly colonized geographical area. Some impacts may directly threaten human health and well-being. For example, coming into physical contact with *P. hysterophorus L.* can potentially result in dermatitis or allergic reactions (Van Wilgen and De Lange, 2011). This study, however, reviews available information to date concerning IAP influence on biodiversity and ecosystem change.

Global biodiversity loss is attributed to, amongst other factors, the exponential rate at which non-indigenous floral and faunal species are spreading on a global scale (Kimothi and Dasari, 2010). According to Kushwaba (2012), the most troublesome IAPs responsible for negatively impacting natural habitats are, in no particular order, *Lantana camara* (tickberry), *Parthenium hysterophorus* (famine weed), *Chromolaena odorata* (Siam weed), *Eichhornia crassipes* (water hyacinth), *Leucaena leucocephala* (white lead tree), *Mikania micrantha* (bitter vine), *Ageratum conyzoides* (Billy goat weed) and *Prosopis juliflora* (mesquite). Nevertheless, the susceptibility of the receiving ecosystem to plant invasions depends on several plant traits of the indigenous flora, such as allelopathic effects, fire resistance, vegetative multiplication, phenotypic plasticity and the degree of homeostasis (Poona, 2008 and Sharma et al., 2005).

Other than plant traits, Poona (2008) also noted plants' competitive population dynamics as a contributing factor. Moreover, Gritti et al., (2006) stated that only one percent of alien plants have the ability to intensely influence and alter the receiving ecosystem. However, the capability of the exotic weed itself to impact and alter an ecosystem largely depends on the biological characteristics of the invaded ecosystem (Hobbs and Humphries, 1995 and Sharma et al., 2005).

Furthermore, the provision of ecosystem resources for indigenous plants is often disrupted by alien plants, subsequently making vast changes in the ecosystem's species composition (Gritti et al., 2006). In other instances, IAP encroachment may impact on the ecosystem's soil properties or even alter the entire cycling of nutrients. More diverse ecosystems tend to be less susceptible to IAP encroachment (Gritti et al., 2006), whilst ecosystems with lower biological diversity are more susceptible to plant invasions (Stohlgren et al., 2003). It is, however, difficult to determine the general influence of biological invasions since most studies focused on the impacts of specific species in small geographic areas (Gritti et al., 2006, Stohlgren et al., 2002 and Van Wilgen and De Lange 2011). The only inference that can deduced from the multiple studies is that less diverse ecosystems are the most vulnerable to biological invasions.

2.6 Managing plant invasions

According to Macdonald (2004) and Olckers (2004), initial attempts to control IAPs in South Africa began in 1913 in the Eastern Cape. The Eastern Cape was in 1913 noted to have incurred a high number of plant extinctions due to IAPs amongst other contributing factors (Masubelele et al., 2009). Adequate management strategies for controlling plant invasions are very costly, which limit their implementation. Figure 2.2 demonstrates the importance of early interventions in controlling invasive species in natural and managed ecosystems to reduce costs. It is more expensive to intervene when the IAP has fully established and dominated the ecosystem. For example, Ezemvelo KwaZulu-Natal Wildlife, who manage protected areas in the KwaZulu-Natal province of South Africa, prioritize the application of the metsulfuron-methyl 600g kg^{-1} herbicide in early October in protected areas to clear *P. hysterophorus*. The early application of the herbicide coincides with early sprouting of the weed, especially the northern regions of the province where the weed has successfully invaded. Early herbicide application on weeds is effective as it kills the plant before it flowers and disperse seeds. The National *Parthenium* Strategy formulated four management zones by defining containment strategies specific to different regions within the country. The four management zones are namely, prevention zones (*P. hysterophorus* does not occur), extirpation zones (areas of early invasion), containment zones (preventing spread to neighbouring zones) and asset protection (managing *P. hysterophorus* in areas where extensive infestations exist). Most of the Zululand area of KwaZulu-Natal falls under the asset protection zone. Yet, the implementation of control management strategies remain advisable at an early stage of spread for IAPs to save costs.

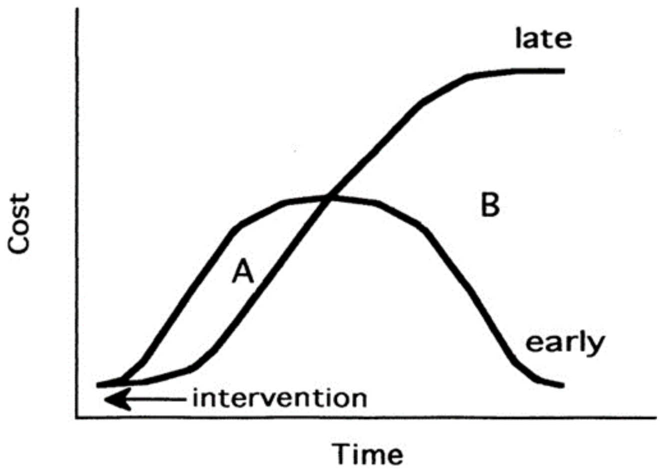

Figure 2.2: A comparison of the cost required to control IAP invasion when applied early (A) and late (B) (Hobbs and Humphries, 1995).

To reduce costs, weed scientists have attempted to predict which natural habitats are potentially vulnerable to invasion (Hobbs and Humphries, 1995). However, the aforementioned (Figure 2.2) has not been much of a success as Hobbs and Humphries (1995) noted the difficulty of using specific plant species' characteristics to identify invisible habitats. Attempts to control exotic taxa are more focused on controlling an individual plant species compared to an overarching control approach (Hobbs and Humphries, 1995). Conservation biologists need to prioritize the management of biological invasions because of the lack of resources (Hobbs and Humphries, 1995), especially for low-income economies.

2.7 Species of interest in this study

Parthenium hysterophorus L. is an invasive annual plant species in the family Asteraceae commonly known as Famine weed, Feverfew, uMbalalazwe, Maria-Maria, and Demonia. It is native to Central and South America and has been expanding its range in South Africa since its introduction in 1880 (Kaur et al., 2014). *Parthenium hysterophorus* is an annual plant species that produces great numbers of seeds (Kaur et al., 2014). The weed is widespread in geographic areas where annual rainfall exceeds 500 mm but it can even germinate in drier environmental conditions due to its dormancy (Goodall et al., 2010). Currently, *P. hysterophorus* can be found in the north-eastern regions of the country. It was first recorded in the Inanda area in KwaZulu-Natal province in 1880 (Hilliard, 1997). It has since been recorded in at least 4 provinces including Limpopo, KwaZulu-Natal, Mpumalanga (Goodall et al., 2010) and North West (Terblanche et al., 2016). *Parthenium hysterophorus* was declared under category 1 of the Conservation of Agricultural Resources Act (CARA) regulations (Act 43 of 1983) and is now placed in category 1b under NEMBA, which declares that this species is a priority for control. There are several cases of *P. hysterophorus* being recognized as dangerous to both human and animal health (Goodall et al., 2010). *Parthenium hysterophorus,* amongst other underlying factors, threatens not only biodiversity and ecosystem services but also economic development and human well-being (Evans 1997; Shabbir and Bajwa 2006; Kaur et al., 2014; Gebrehiwot and Berhanu 2015). Studies on the effect of *P. hysterophorus* on diversity have revealed that there is a negative relationship between *P. hysterophorus* cover and plant species diversity (Dogra et al., 2010; Timsina et al., 2011; Gebrehiwot and Berhanu, 2015). Besides posing a major threat to biodiversity, environmental impacts caused by *P. hysterophorus* include irreversible changes in vegetation (Jayachandra, 1971). Few to no indigenous species occur in areas where there is high *Parthenium* infestation (Gebrehiwot and Berhanu 2015). *Parthenium hysterophorus* invasion has exceeded the predicted weed invasion estimations. The extent of alien invasion is typically recorded across quarter-degree grid cells (cells of approximately 25 x 25 km) according to the Southern African Plant Invaders Atlas (Terblanche et al., 2016). However, *P. hysterophorus* has extended its range from 62 cells in 2007 to 76 cells in 2016 (Terblanche et al., 2016). It has been recognized as a potential driver of biodiversity loss due to its high reproductive and dispersal characteristics (Timsina et al., 2011). *Parthenium hysterophorus* can outcompete native vegetation (Strathie et al., 2011) and its aggressiveness towards native and non-invasive species contributes to the disturbance of ecosystem services.

2.8 *Parthenium* invasion in Ezemvelo KZN Wildlife reserves

The northern region of KwaZulu-Natal experiences a significant percentage of *P. hysterophorus* encroachment. The spread of *P. hysterophorus* in KwaZulu-Natal is propelled by natural and anthropogenic factors, calling for immediate and effective eradication and/or control measures. Since the *Parthenium* outbreak in the KwaZulu-Natal Province, Ezemvelo and its counterparts formulated nine recommendations for the management of *Parthenium* invasions within the Ezemvelo protected areas and adjacent to its boundaries (McDonald and Lee 2013). The recommendations are summarised as follows:

2.8.1 To use every opportunity, available resources and support from international programmes in fighting *Parthenium*.

2.8.2 To run a progressive awareness campaign with all reserve staff to enable them to identify *Parthenium* at its early life stages (vegetative state) before flowering.

2.8.3 To continuously adapt management programmes.

2.8.4 To review all present management strategies in order to ensure that these are not further spreading *Parthenium* seeds. In particular, mowing using a tractor should be revisited as this strategy is known to aid the spreading of *Parthenium*.

2.8.5 To execute a programme of reducing herbivore populations in order to avoid overgrazing in all reserves, since the healthy perennial cover is a critical factor for preventing alien invasion.

2.8.6 To organize effective programmes for washing-down vehicles and equipment in order to reduce the unintentional spread of *Parthenium* seeds.

2.8.7 To recommend herbicide control programmes focusing on removing *Parthenium* from at least 20m from the reserve boundary and for a distance of about 5 km from the reserve entrance, with repeated spraying every growing season.

2.8.8 To urge the national government to provide long-term funding for the regulation of *Parthenium*. In addition, to promote rapid implementation of a large-scale biological control programme at a national scale.

Herbicides are a useful option for the farmer, and the vegetation manager in controlling IAPs such as *P. hysterophorus* (Marshall, 2001). There are two scenarios in which herbicides are used; a) in most situations herbicide is used to control several targeted plant species in a particular area; b) there is a single target species and all other plants present are non-targets (Marshall, 2001). The impact of chemicals on the environment and non-target species have been noted since the early 1960s (Kohler and Triebskorn, 2013). The use of chemicals to control invasive species were found to have caused serious damage to populations of non-targeted species including wildlife (Kohler and Triebskorn, 2013). There is very little information on their impact on plant species diversity, possibly due to difficulties in separating the effects of chemicals versus other factors in explaining declining floral diversity (Kohler and Triebskorn, 2013).

Ezemvelo KZN Wildlife annually reports on their achievements in conserving the province's biodiversity. On the 28th of August 2013, a forum workshop focusing on KwaZulu-Natal’s invasive species was attended by Ezemvelo KZN Wildlife’s ecological advice manager, Mr. Ian Rushworth, who presented a scientific approach to deal with the apparent invasibility of

P. hysterophorus. Suggestions were made around the minimisation of the ecosystem risk to invasion, the establishment of secure control measures in protected areas, and lastly, to ensure cooperation between local, national and global role-players in executing control plans and proposed strategies. The 2017/2018 report by Ezemvelo KZN Wildlife clearly indicates the execution and success of the *Parthenium* project. A total budget of R5 000 000 was set aside to clear the famine weed during the 2017/2018 period. In summary, the program created 171 employment opportunities resulting in total expenditure from the budget of R4 383 489. The *P. hysterophorus* clearing program was reported to be a great success, where, the Expanded Public Works Programme (EPWP) was involved in clearing several designated sites. The short- and short-medium term effectiveness of their control initiative is, however, not yet understood. It is necessary to evaluate the effectiveness of control methods that are currently being implemented. This, therefore, opens up to potential studies for future research.

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CHAPTER 3

Spatial Gradient of *Parthenium* Infestation

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3.1 Abstract

This study explores the use of a one-class support vector machine algorithm in mapping an exotic weed, *Parthenium hysterophorus*. The weed has extensively invaded the northern region of KwaZulu-Natal where many protected areas of the province are located. The invasive weed threatens the ecological integrity of KwaZulu-Natal's protected areas, which are mostly managed by Ezemvelo KZN Wildlife (EKZNW). *Parthenium hysterophorus* does not only impact on plant communities, but also animals and human health. It is, therefore, important for EKZNW to spatially understand *P. hysterophorus* extent of encroachment before setting up a budget for eradication measures to achieve a *P. hysterophorus* free buffer area. The aim of this study was, therefore, to detect the extent of encroachment of *P. hysterophorus* in the buffer zone of Hluhluwe-Imfolozi Park, a big-five game reserve. Defining the exact threat of *P. hysterophorus* outside a protected area stemmed from the visual difference of the level of infestation before entering Memorial Gate to the protected area. This has raised an ecological concern as buffer zone management programs should not be isolated from the protected area management plans in controlling weeds and optimizing the dominance of native flora. This study has reported an infestation level of the target weed that management still has great potential to control. Three map outputs were produced, the first with the use of spectral bands only, the second map only made use of computed vegetation indices and the third map was a combination of both spectral bands and vegetation indices. The map with the highest classification overall accuracy of 81.97% made use of both spectral bands and computed vegetation indices. Other land cover classes were masked out for a binary classification and the total cover of native grass species was 119,89133 km^2, compared to 129,545325 km^2 of *P. hysterophorus* within the area of study. This study confirms extensive encroachment of the target species, which threatens the ecological integrity of the protected area. To prevent more ecological damage, the current management strategies used by EKZNW within the protected area to combat the spread of invasive alien plants should also be applied within the buffer zone to minimize biotic stress.

Keywords: one-class support vector machine, sentinel 2 multi-spectral instrument, google earth engine, spectral bands, vegetation indices, buffer zone management, ecological sensing, weed mapping

3.2 Introduction

Examining invasive alien species' spatial distribution patterns is increasingly gaining popularity in the ecological remote sensing and geographic information systems (GIS) research arena [14, 29]. Invasive alien species have been identified as the second greatest driver of habitat destruction by outcompeting native biodiversity [3,33]. Biological invasions have deleterious impact on water quality, microclimate, soil nutrients, agricultural economies, and fire regime [14], listing them amongst the most prominent influencers of ecological change. Gallo and Waitt [10] noted a 14% annual increase of global biological invasions in communal areas, which consequently is capable of transforming ±1861.554 hectares of land in wildlife ecosystems on a daily basis. This raises concerns for policymakers, natural resource managers, and ecologists regarding the lack of invasive species spatial distribution maps to quantify the extent of infestation at a local level [10, 14,21]. The spatial monitoring of exotic weeds facilitates decision-making for devising and implementing rigorous measures to alleviate adverse ecological and socio-economic impacts [1, 4, 32]. Several studies have revealed the importance of alien plant invasion maps as an indicator for early warning systems and ensuring prompt responses to effectively manage newly invaded habitats [4, 29, 31]. Moreover, the provision of alien invasive species distribution maps caters for an informed understanding of all potential factors accountable for accelerating the spatial distribution of biological invasions at large scales. However, considerations by Thriller et al., [31] suggest a cooperative approach in utilizing distribution maps, for example, optimizing quarantine methods in high-risk regions, as it is very challenging and costly to implement control measures subsequent to invasion.

For over thirty years, experimental studies in ecological sciences have been exploring the use of remotely sensed information to achieve conclusive results [12]. Since the mid-1990's remotely sensed data has become an important tool in studying invasive alien plants [12]. Applications used in remote sensing seek to acquire information on the earth's surface without demanding physical contact [12], opportunely suitable for large scale mapping [1]. A simple and ecologically viable remote sensing procedure to detect pre-invasion, present-day invasion, and possible future dimensions of spread entail the use of temporal, spectral, and spatial information [12, 29].

There are indications that plant communities that are more diverse have higher susceptibility to invasion [7]. Even though, previously, less diverse plant communities were believed to be more susceptible to invaders but this has been proven otherwise [7]. On this account, spatial heterogeneity is very challenging for independent use of remote sensing applications in detecting and mapping IAPs that prevail as either understory species or as invaders that do not dominate the canopy [21]. Most common alien invasive plants are defined by Joshi et al., [14] and Masocha and Skidmore [21] as heterogeneous-canopy invaders or indistinct understory flora. This contributes to less spectral information during data capture of passive remote sensors. To overcome this drawback, a robust image classification algorithm that fully detects spectral information of remotely sensed data should be employed [21]. The One-Class Support Vector Machine (OCSVM) classification algorithm has demonstrated superior potential in discriminating spatial patterns of a target species that exist in–highly heterogeneous environments [19, 20, 34]. *Parthenium hysterophorus* L. is amongst many other alien invasive species that occur as an understory species in diverse ecosystems [16]. Therefore, this study applies the popular OCSVM algorithm, which has been advantageous for remotely mapping vegetation in previous studies [19, 34]. In addition, the dissemination of contemporary multispectral sensors is credibly known for its improved capabilities of detecting and mapping alien invasive plants [25].

The traditional, labour-intensive nature of acquiring field-collected botanical information has progressed with the development of technological applications [17, 24]. Due to the difficulties of conducting vegetation sampling at ground-level, and at a large scale, remote sensing products have been developed to conduct contemporary, spatial vegetation distribution research [1]. Initially, the mapping of IAPs that relied on field-based surveys was expensive [32], unsustainable [25], and needed specialists' inputs [1]. Other difficulties include the inaccessibility of certain areas of the study site [24], particularly in remote regions [25]. With the development of remote sensing applications, the mapping of invasive alien species has become cost-efficient and practical [24]. As a result, satellite remote sensing is becoming more of a credible substitute for mapping invasive flora as compared to the more traditional approaches [3, 17, 25, 32].

The present study sought to determine the actual threats of *P. hysterophorus* outside Hluhluwe-Imfolozi Park by quantifying the extent of infestation with the use of remote sensing applications. Specifically, this study examines the capability of the freely available, Sentinel 2 Multispectral Instrument (MSI) remote sensing imagery to determine the spatial distribution of *P. hysterophorus* within the study area. Although the newly launched Sentinel 2 MSI has been explored in spatially presenting *P. hysterophorus* infestations [1, 15], the use of a singular class classification method is distinctly understudied. Furthermore, a recent study by Royimani et al., [25] recommended the use of Sentinel 2 imagery jointly with an appropriate feature selection approach for future research studies in mapping invasive alien plants (IAPs). This is attributed to the high spatial, spectral, and temporal resolution characteristics of the multispectral sensor. *Parthenium hysterophorus* grows to a height of 2 metres and is effectively controlled inside the reserve, which makes it difficult to present the extent of invasion inside the reserve. The high level of infestation that was observed outside the reserve brought into question the extent of encroachment. The aforementioned remote sensing applications, in this case, were evaluated in order to assist plant invasion conservationists of EKZNW to achieve a *P. hysterophorus* free buffer area.

3.3 Materials and Methods

3.3.1 Description of study site

This study was conducted in one of the oldest game reserves in Africa, Hluhluwe-Imfolozi Park (HiP) and its surrounding area (10 km buffer zone) (Figure 3.1). Specifically, HiP is an incorporation of the Hluhluwe Game Reserve and the adjacent iMfolozi Game Reserve. Due to greater *P. hysterophorus* infestations in Hluhluwe [25], this study focused on mapping *P. hysterophorus* threats outside the Hluhluwe Game Reserve border. The whole park is located approximately 20 km northwest of Mtubatuba, at the juncture of the coastal area and foothills of KwaZulu- Natal’s mountainous range, between 27° 59′ 55″ and 28° 26′ 00″S, and between 31° 41′ 40″ and 32° 09′ 10″E. It has an altitudinal range of 70-580 m above sea level [9] and is 96000 hectares [11]. The rainfall in HiP is highly seasonal with most rains occurring between October and March [9, 13]. Annually, the park receives 390-1250 mm of precipitation [13], with mean annual rainfall ranging from 985 mm at higher altitudes to 650 mm at the lower altitudes [9]. Annual temperatures vary between ±13 °C to ±35 °C and are also strongly influenced by altitude [9, 13]. The study area was selected to assist in the achievement of a *P. hysterophorus* free area, as the park epitomizes formal conservation in the KwaZulu-Natal province, South Africa.

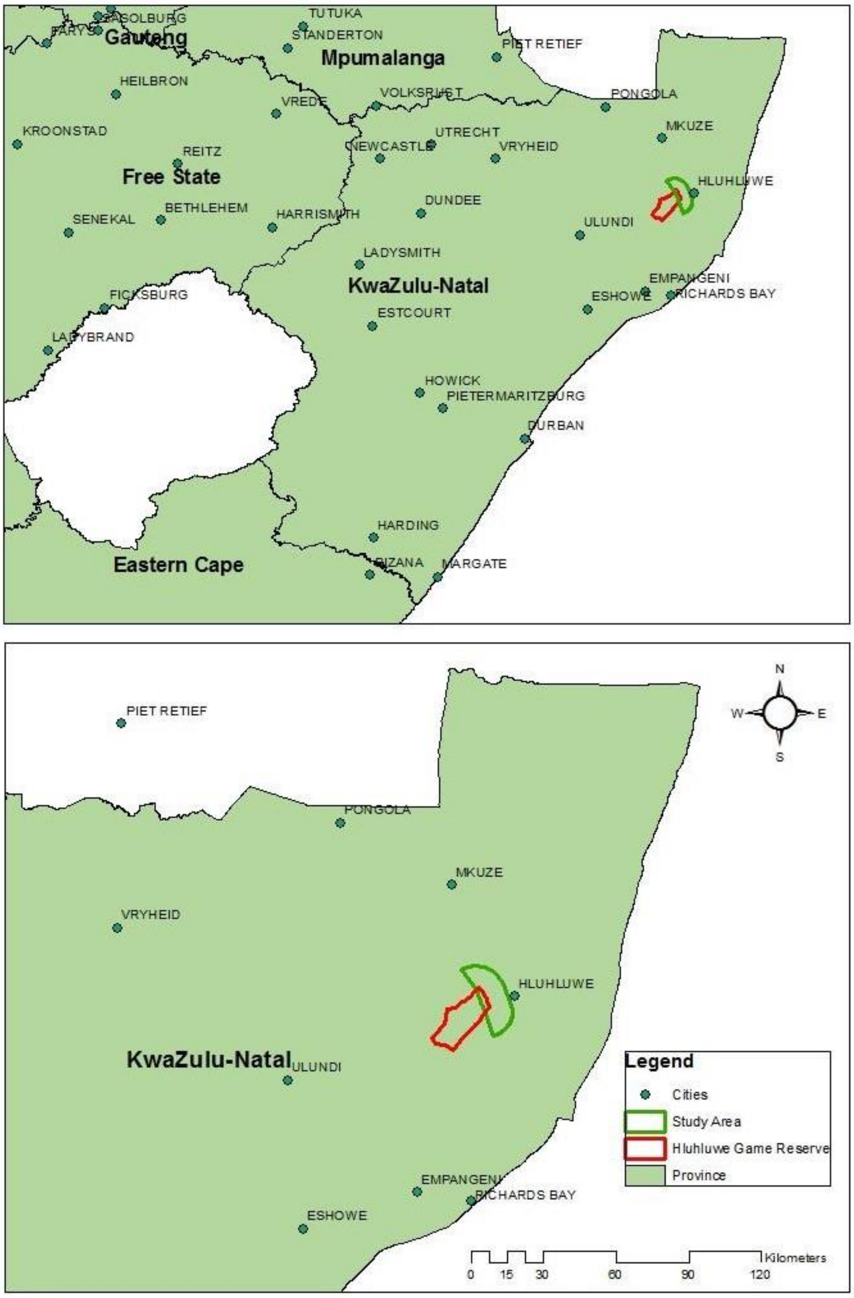

Figure 3.1: Ten km buffer area with *Parthenium* extent of encroachment. The Hluhluwe Central Business District (CBD) is located straight-after the boundary of the selected buffer area, hence, this study only focuses on the 10 km buffer of the protected area.

3.3.2 Field data collection

A ground-level vegetation observation for detecting and mapping IAPs with the use of remotely sensed information requires discrimination data of the target species. Spatially explicit information on the land surface was extracted from remotely sensed satellite data. Point observations on the ground were conducted with the use of a Trimble GeoXH 6000 Global Positioning System (GPS) device with a sub-meter accuracy to discern the invasive plant species of interest namely, *P. hysterophorus*. Points, where there is homogenous existence of *P. hysterophorus*, were randomly recorded throughout the study site. The preferred plot size of the target species to be recorded was 10 × 10 m. This is to circumvent the overestimation of the target species in patches where there is less *P. hysterophorus* percentage cover, as Sentinel 2 data products prefer spatial resolution at 100 m^2. Considering the mountainous terrain of the study site, accessibility was restricted. Therefore, 100 m^2 *P. hysterophorus* cover was only sampled in accessible areas of the study site.

Co-ordinates were collected late summer (February 2020), following spring and summer rainfalls when vegetation was fully developed for the discrimination of *P. hysterophorus*. The geographical reference information of the target species was used as a single land cover class to discriminate it from background co-existing plant communities. Centre GPS co-ordinates measured in each patch were recorded and used to create a point map in ArcGIS 10.4 software. Point values are essential to run an accuracy assessment of its correspondence to the acquired satellite imagery. The point values were then converted into polygons of interest (POI) in the ArcGIS 10.4 software as a creation of training and validation polygons. A 70/30 training sets technique was used from the total number of polygons of interest that were acquired during field-data collection.

3.3.3 Satellite imagery acquisition

The European Space Agency's (ESA's) neoteric launch of Sentinel 2 Multi-Spectral Instrument (MSI) has permitted the use of technological advancements for advanced spatial monitoring of terrestrial and coastal ecosystems since June 2015. The Sentinel 2 MSI is characterized by an advanced spectral resolution bandwidth, rendering high-resolution data through world observations of terrestrial and coastal ecosystems [18]. Sentinel 2 MSI has fine spectral bands, thirteen in total, therefore rendering an improved ability to present spatial variability amongst target species [18]. Ranging from the visible and the near-infrared (NIR) to the short-wave infrared (SWIR) regions of the electromagnetic spectrum (EM), the 13 spectral bands have a spatial resolution of between 10 to 60 metres. Of the 13 spectral bands, only bands 2, 3, 4 and 8 acquire satellite imagery with a 10-metre spatial resolution [18] and therefore were relevant for recording 100 m^2 *P. hysterophorus* cover during the field survey. The imagery is known to have a swath width of 290 km and a high revisit time of 5 days, under cloud-free conditions. Furthermore, Sentinel 2 MSI retains three bands in the red-edge region at 705, 740, and 783 nanometres of the electromagnetic spectrum, which were not found in previous multi-spectral sensors. These three bands have therefore improved multi-spectral remote sensing specifically for discriminating indistinct vegetation patterns [1]. With sufficient availability of quantitative spatial information on the freely accessible United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) centre, Sentinel 2 MSI satellite data covering the study area was acquired for analysis.

3.3.4 Pre-processing of Sentinel 2 MSI imagery

Remotely sensed imagery consists of atmospheric inadequacies due to the scattering and/or absorption of electromagnetic radiation [18]. As a result, satellite images require an atmospheric correction method in sequence to retrieve accurate spectral reflectance information of a surface. The atmospheric correction method performed on the acquired Sentinel 2 MSI imagery for this study was the image-based, dark-object observation (DOS) method which is available on the ENVI software [5, 18]. The application of the DOS correction method demands orthorectified imagery, which the Sentinel 2 MSI data sources readily deliver. Level 1C (L1C) Sentinel 2 products contain top of atmosphere (TOA) reflectance information, in the Universal Transverse Mercator (UTM) projection and are geometrically and radiometrically corrected [2].

3.3.5 Vegetation indices

Several studies on plant invasive species [1, 22, 26] substantiate the remarkable performance of using vegetation indices (VIs) in providing reliable spatial variations of plant communities. The selected VIs for this study as shown in Table 3.1 are spectrally altered to improve the detection of vegetation properties.

Table 3.1: Computed Vegetation Indices

Indices	Computation	Reference(s)
Normalized Difference Vegetation Index **(NDVI)**	(NIR - Red)/(NIR + Red)	[8], [22] , [24], [26]
Soil Adjusted Vegetation Index **(SAVI)**	((NIR - Red) * (1 + L))/(NIR2 + Red + L)	[1], [8], [24]

Difference Vegetation Index **(DVI)**	NIR - Red	[8], [26]
Green Normalized Difference Vegetation Index **(GNDVI)**	(NIR - Green)/(NIR + Green)	[26], [30]
Enhanced Vegetation Index **(EVI)**	2.5 * ((NIR - Red)/(1 + NIR + 6Red - 7.5Blue))	[1], [25]
Green Chlorophyll Index **(G Chl Index)**	(NIR/Green) - 1	[1], [28]
Simple Ratio Index **(SRI)**	(NIR/Red)	[26], [30]
Green Difference Vegetation Index **(GDVI)**	NIR - Green	[26]
Green Ratio Vegetation Index **(GRVI)**	NIR/Green	[26]
Infrared Percentage Vegetation Index **(IPVI)**	NIR/NIR + Red	[8], [26]
Normalized Difference Water Index **(NDWI)**	(Green - NIR)/(Green + NIR)	[24], [30]
Greenness Index **(GI)**	Green/Red	[8], [30]

3.3.6 Image classification

The use of classification procedures has been extensively explored in ecological science to statistically analyze information [6]. Traditional classification procedures that are commonly used in remote sensing are prone to low accuracies, have complex imagery specifications, and require multi-class training data [19, 34]. To circumvent the time required to conduct field surveys, collecting reference data for several classes other than the target species has necessitated the use of an OCSVM classification. According to Xu et al., [34], amongst all the algorithms used for One-Class Classification (OCC), OCSVM has progressively gained popularity and has great potential in image classification studies, primarily in mapping vegetation. With the strengthened capability of discriminating *P. hysterophorus* after calculating the NDVI, SAVI, DVI, GNDVI, EVI, G Chl Index, SRI, GDVI, GRVI, IPVI, NDWI, and GI (Table 3.1) , further application of the OCSVM classification algorithm ensures the extraction of the weed’s spatial distribution patterns within the study area. Statistically, the overall accuracy of using OCSVM classification at a localized level is 88.59% [34]. On the other hand, disadvantages of running classifications on satellite imagery with heterogeneous land cover classes are that errors can be introduced in studies where every class is not accurately defined during reference data collection [34]. Therefore, to circumvent classification inaccuracies, it is only the class of interest that will be spatially discriminated to determine *P. hysterophorus* extent of invasion. Also, the application of a one-class classification does not require additional costs [20, 34], hard labour, or prolonged working hours [34], correspondingly making it more practical to use [19]. The OCSVM remote sensing image classification was implemented in the Google Earth Engine (GEE) computing platform.

The GEE platform is a freely available and user-friendly application software [23] that allows the processing and analyses of geospatial information at any defined scale. Shelestov et al., [27] noted the GEE platform to offer a wide range of robust classification algorithms, namely, random forest, decision tree, probabilistic Naïve Bayes, and the support vector machine. The classification performance of mapping vegetation on the GEE platform is expected to be greater than 70% when using a combination of several variables, such as geographic ancillary information, and/or spectral VI computation [23].

3.3.7 Accuracy assessment

An accuracy assessment is essential for classified remotely sensed imagery to quantitatively examine the similarity between a classified image and a reliable source of accurate ground truth data. In this study, a conventionally used and reliable accuracy assessment method is the confusion matrix that generates the kappa coefficient. The overall accuracy (OA) is a percentage measurement of the classification performance, examining the total number of correctly classified classes in comparison with the acquired total of validation data. When incorporating a 70/30 training set technique, 70% of the ground reference dataset is applied in training the OCSVM classifier and the remaining 30% is essential for running the OA of the OCSVM. The producer's accuracy (PA) is derived by a fraction of the total number of accurately classified pixels, over the total number of ground-referenced pixels used in the study. On the other hand, the user's accuracy (UA) is a percentage representation of how reliable the classified map is, whereby the total number of accurately classified pixels is a fraction of the total number of rows.

To calculate the producer's and user's accuracy of the image:

$$PA(\%) = 100\% - error\ of\ omission\ (\%)$$

And

$$UA(\%) = 100\% - error\ of\ commission\ (\%)$$

The kappa coefficient quantifies the overall statistical agreement between classified and ground-referenced information. The kappa coefficient ranges from zero to one, whereby a measurement closer to one signifies that the classification algorithm is more accurate.

3.4 Results

3.4.1 Classification accuracy evaluation

The classification accuracy was assessed for the different variables used to generate *P. hysterophorus* distribution maps. The overall classification performance (Table 3.2) of Sentinel 2 MSI bands was 75.41%, 73.77% for the computation of vegetation indices, and improved accuracy of 81.97% and a Kappa coefficient of 64% for the combination of both Sentinel 2 MSI bands and VI computation.

Table 3.2: Confusion accuracies derived from (a) sentinel bands, (b) vegetation indices, (c) bands, and vegetation indices in mapping *Parthenium* distribution.

	Bands	Vegetation Indices	Combined variables
Confusion Matrix	[[23,7], [8,23]]	[[22,8], [8,23]]	[[25,5], [6,25]]
Overall Accuracy (%)	75.41	73.77	81.97
Producer's Accuracy (%)	74.19	74.19	80.64
User's Accuracy (%)	76.67	73.33	83.33
Kappa coefficient	0.51	0.48	0.64

3.4.2 *Parthenium* infestation levels

Where the classification accuracy was highest, *P. hysterophorus* distribution was a dominant cover species in comparison to other species. According to Figure 3.2, infestation levels of the target weed within the 10 km buffer area of a protected area (Hluhluwe-Imfolozi Park) seem to have progressed and become problematic for both the natural environment of the buffer area and the ecological integrity of the protected area. Local community dwellers are also despondent about the current threat *P. hysterophorus* poses to their well-being. The extensive distribution in Figure 3.3 can be also attributed to mapping the weed post-summer rainfalls when it is most remotely detectable due to large homogenous patches.

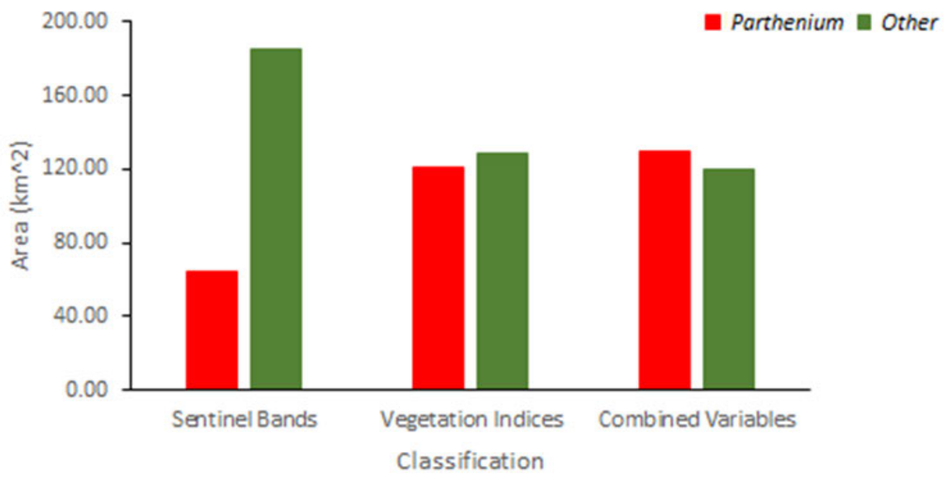

Figure 3.2: Total area in kilometres squared by class (*Parthenium* and other species) within the study area.

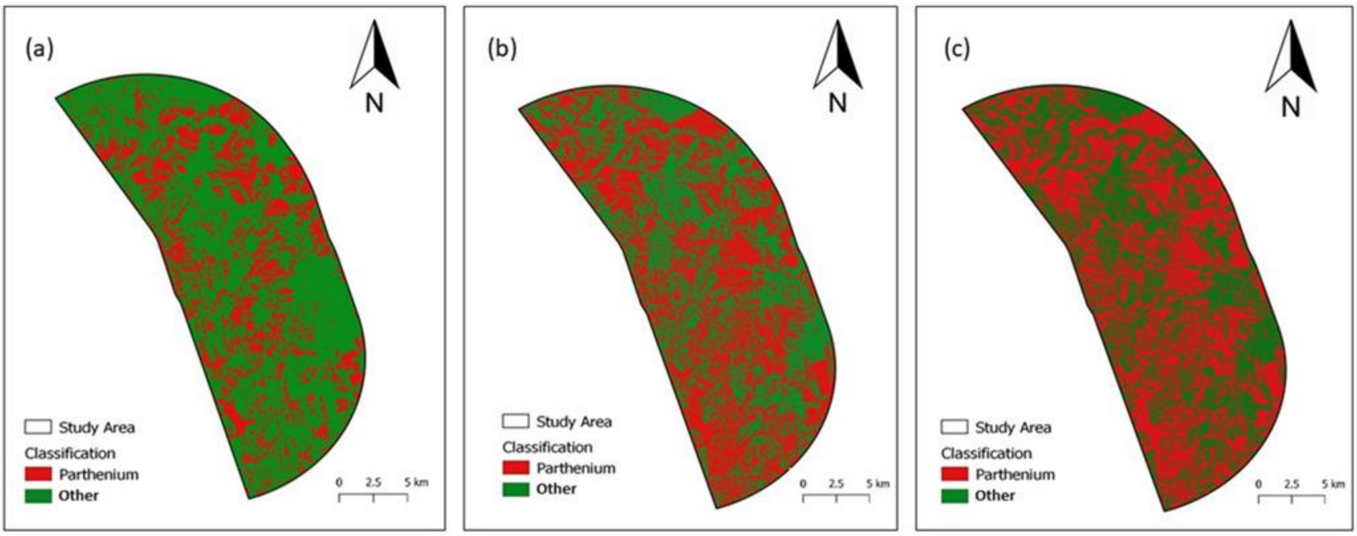

Figure 3.3: Detected spatial distribution of *Parthenium hysterophorus* within a 10 km buffer area of Hluhluwe-Imfolozi Park. The map was derived by the use of (a) sentinel bands (b) vegetation indices (c) sentinel bands and vegetation indices.

The present study aimed to spatially evaluate *P. hysterophorus* infestation levels of a 10 km buffer zone of Hluhluwe-Imfolozi Park. The results (Figure 3.2 and 3.3) show the acquired potential of Sentinel 2 MSI imagery in mapping the spatial distribution of *P. hysterophorus* with the use of a one-class support vector machine algorithm. The detection and discrimination of *P. hysterophorus* encroachment in Figure 3.3 can be used to advise weed management programmes for EKZNW as it determines the actual threats in the 10 km buffer outside the reserve.

3.5 Discussion

This study reveals the capability of the GEE platform in performing a robust one-class classification algorithm when making use of Sentinel 2 MSI satellite data, in spatially detecting exotic flora. The ability of methods using different variables in detecting *P. hysterophorus* were compared in this study. Kiala et al., [15] stated the inadequate application of using spectral bands when mapping IAPs and Matongera et al., [22] highlighted the unreliable use of vegetation indices in isolation when detecting/mapping IAPs. Several studies in ecological remote sensing [1, 22, 15] advised on incorporating different variables to improve mapping accuracies. Complementing computed VIs with other variables is known to be beneficial [22] as it ensures a decreased reflectance of soil and atmospheric particles. The incorporation of both spectral bands and VIs significantly improves mapping accuracies in vegetation delineation [15, 22]. Findings in this study also demonstrated the capability of the OCSVM classification algorithm in accurately discriminating plant landcover types. Results in Figure 3.3 clearly distinguish the vegetation communities of the binary classification within the study area, therefore, reporting an efficient classification performance of the robust OCSVM.

The extent of invasion by *P. hysterophorus* in the buffer zone consequently influences the ecological functioning of the protected area. In theory, buffer zones are an additional shield in strengthening the conservation of biological diversity inside the protected area. It is, therefore, mandatory for EKZNW to examine the extent of encroachment in the peripheral regions of their protected areas which are susceptible to biological invasions. Defining the exact threat of IAP encroachment is valuable for environmentalists, decision-makers and ecological scientists in establishing suitable mitigation approaches. The vast extent of *P. hysterophorus* encroachment in the peripheral regions of Hluhluwe-Imfolozi Park (Figure 3.3) confirmed the visualized level of infestation, which is a great ecological concern when approaching the Memorial Gate to the protected area.

It has been acknowledged that EKZNW currently has IAP management strategies that are regularly implemented inside their protected areas. However, there is a need to prioritize buffer zone management programs, concurrently with protected area management plans in controlling weeds and optimizing the dominance of native flora. An improved mapping accuracy of 81.97% when combining sentinel bands and VIs in this study informs EKZNW in spatially understanding the threat posed by the famine weed outside the protected area. With an attempt to achieve a *P. hysterophorus* free buffer area, EKZNW requires an additional budget for eradication measures, and the current management strategies that are being implemented inside the protected area should be assessed if they are effective and if they do not harm other non-targeted coexisting plant species.

3.6 Conclusions

The Sentinel 2 MSI satellite imagery exhibited immense capability in spatially discriminating *P. hysterophorus* with the use of a singular class classification method on the GEE platform within a 10 km buffer zone of a protected area, Hluhluwe-Imfolozi Park. Combining sentinel spectral bands and suitable vegetation indices optimize vegetation mapping and improved overall classification accuracies. Freely available remotely sensed data and robust image classification algorithms have shown an improved capability in discriminating vegetation features on the ground. The study could be used to inform the management of Ezemvelo KZN Wildlife in drafting an effective weed clearance strategy to achieve a *P. hysterophorus* free buffer.

3.7 Acknowledgements

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CHAPTER 4

Parthenium hysterophorus Control in Hluhluwe-Imfolozi Park and herbicide impact on non-targeted plant communities

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4.1 Abstract

The effectiveness of applied weed management strategies has gained a lot of attention from invasion plant ecologists in South Africa. The vast and continued spread of exotic flora has prompted policymakers at government institutions to develop environmental legislation regulating the eradication or control of invasive alien plants (IAPs). The present study evaluated the herbicidal efficacy of the metsulfuron methyl used by Ezemvelo KZN Wildlife (EKZNW) in controlling a severe invader, *Parthenium hysterophorus* (famine weed). The study was conducted in Hluhluwe-Imfolozi Park, an area of significant biological diversity and ecological importance, and its buffer zone. Plots were arranged in a complete randomized block design, with three replicates per site (inside and outside the reserve). Short to medium term changes in *P. hysterophorus* and non-target species were monitored in 100m^2 plots' per treatment viz. control and uncontrolled. Herbicidal efficacy was evaluated based on the mortality rate of the famine weed after spraying the recommended dose of the herbicide. Species composition data of the non-targeted species was recorded in each plot, before and after spray. Herbicide application inside the reserve reduced *P. hysterophorus* cover by 54% while in the buffer zone, the reduction was 87%. The non-target species cover ranged between 70% and 95% in both sprayed and unsprayed treatments. The study confirmed that the herbicide control used by Ezemvelo KZN Wildlife was effective against *P. hysterophorus* in both the reserve and buffer zones with minimal damage to non-target species. Short to medium term results reported a successful reduction of the weed to manageable levels, however, opportunities for improvement should be explored in future research studies.

Keywords: ecosystem invasion, herbicide efficacy, metsulfuron methyl, chemical control, protected area, ecological restoration, species diversity, Ezemvelo KZN Wildlife.

4.2 Introduction

Plant invasion ecologists have documented that invasion by alien plants is the second greatest transformer of natural habitats worldwide (Pejchar and Mooney, 2009). Ecosystems require continuous and effective management interventions to minimize potential impacts on biodiversity after invasion by alien species. The success of management approaches for controlling invasive species is challenged by limited availability of information on high-priority aspects, such as general biodiversity outcomes that are currently understudied (Downey et al., 2010). Also, procedures undertaken to develop effective weed management plans at the regional and national level are hindered by the proposed methods of approach (Anderson et al., 2003). Inadequacies in weed management plans at regional and national levels are attributed to localized and uncoordinated application of weed control methods (Anderson et al., 2003). However, after the introduction of herbicide-based weed management strategies in the 1940s (Mohler et al., 1997), controlling weeds, especially those spread by seeds, has been effective. Herbicide control is an indispensable component in controlling alien invasive plants (Peterson, 1999), helping to minimize the spread of alien species in developed and developing countries (Heap, 1997). In the past 45 years, alien invasive plants have become less resistant to herbicides (LeBaron, 1989), which previously had been a major disadvantage (Heap, 1997). This, however, does not indicate the non-existence of herbicide-resistant weeds (Peterson, 1999 and LeBaron, 1989). Herbicide-based strategies offer poor prospects of success over the long-term, for several reasons, but permanent reliance and expense are their biggest weakness. They may be cost-effective in the short term but expensive over the long term. Weeds will always thrive to dominate in stochastic environments (LeBaron, 1989). The most effective and reliable method of control in order to circumvent deleterious ecological impacts requires early detection and rapid control measures with the aim to avert dominance (Pluess et al., 2012). However, attempts to successfully eradicate invasive species are not only difficult but time consuming with excessive use of limited resources (Rejmἀnek and Pitcairn, 2002). As a result, herbicides have been adopted as a primary control method due to their cost-effective nature (Heap, 1997). The ability of a weed to resist chemical control is species dependent (Peterson, 1999).

Parthenium hysterophorus L., commonly known as famine weed, is a category 1b invasive alien plant that is rapidly spreading across KwaZulu-Natal. *P. hysterophorus* is noted by Adkins et al., (2010) and Adkins and Shabbir (2014) to be very difficult to control with the use of a single method. Several management strategies i.e. mechanical, biological, cultural, and chemical have been tested to control the spread of *P. hysterophorus* in native plant communities (Adkins and Shabbir, 2014). The four management approaches have advantages and disadvantages in terms of their ability to control *P. hysterophorus* in the long term. Mechanical approaches entail the manual extraction of *P. hysterophorus*, prior to its flowering stage (Dhileepan, 2009). However, manually removing *P. hysterophorus* is only restricted to small-scale invasions in communal areas (Dhileepan, 2009), whilst Shabbir et al., (2013) suggested a structured budget to cover labour costs considering the apparent high magnitude of *P. hysterophorus* infestations globally. A disadvantage of this method is that the manual removal of the famine weed poses health hazards for the contractors. For example, direct contact during handling of *P. hysterophorus* may potentially result in an itchy inflammation of the skin, hay fever, or the development of dark spots. Consequently, mechanical approaches in controlling *P. hysterophorus* are not entirely endorsed (Dhileepan, 2009). Applicable mechanical approaches for interim management of *P. hysterophorus* at a regional level include the use of earth moving machinery, gashing, and cultivating common crops on vacant land (Dhileepan, 2009). The aforementioned physical approaches positively influence the re-establishment of *P. hysterophorus* in the long term, therefore are not sustainable weed management strategies. Biological control methods entail the intentional introduction of an agent that will act against the existence of a problematic target species. The agents act as natural enemies and examples include parasites, insects and pathogens, that when introduced, become a nuisance to the target weed. Biological control methods are recommended as they are cost effective and effective once established (Fowler et al., 2000). The likelihood of environmental risks and ecological consequences after the introduction of weed control agents are the main disadvantage of implementing biocontrol methods (Fowler et al., 2000). This also results in another disadvantage which is the length of time before these biological control agents can be released because of the lengthy research and testing. It is, however, challenging to predict or approximate the significance level of desecration (Fowler et al., 2000). On the other hand, cultural control methods as stated by Adkins and Shabbir (2014), necessitate the removal of prolific seeds from, for example, shoes, clothes, and vehicles. This acts as the first line of defence in reducing the dispersal of exotic flora and the risk of increased densities. Chemical control measures are known to be most effective, but very labour-intensive, time-consuming, and expensive (Dhileepan, 2009). Herbicide application efficacy, however, is determined by the period of application and the selection of the herbicide being used (Dhileepan, 2009).

Nevertheless, *P. hysterophorus* control has been fairly successful with the use of both chemical and biological methods i.e. applying selective herbicides, bacteria, fungi or insects originating from other regions of the world, naturally suppressing the competitive ability of *P. hysterophorus* (Adkins and Shabbir, 2014). For example, Dhileepan (2009) mentioned the introduction of the *Puccinia melampodii* Dietel & Holway rust fungus in 1995 to biologically control *P. hysterophorus L.* in South Africa. Kaur et al., (2014), on the other hand, only found the utilization of biological control methods to be successful when managing *P. hysterophorus*. Goodall et al., (2020) motivated for the continuous implementation of integrated management strategies for long-term extirpation results in controlling *P. hysterophorus*, such as biological control, veld management, and animal management, more specifically, on game and livestock farms. The abundance of fungal plant pathogens or exotic insect species that are natural enemies to *P. hysterophorus* should be maximized in an ecosystem to achieve the highest mortality results. Adkins and Shabbir (2014) reviewed *P. hysterophorus* management techniques and concluded only an integrated weed management (IWM) system will achieve the best results of *P. hysterophorus* mortality in invaded areas. The IWM approach is an integration of all management approaches that can possibly be used with no economic constraints. However, in several regions, such as Ethiopia, India, and South Africa (Dhileepan, 2009), it is evident that a single method of control does influence *P. hysterophorus* mortality (Adkins and Shabbir, 2014).

Metsulfuron-methyl (Figure 4.1) is a wettable powder herbicide for the control of certain woody invaders and broadleaf weeds in veld and conservation areas. The metsulfuron-methyl 600 g kg-' formulation is commercially available under several trade names, one of which is Forester®, manufactured by Arytsta LifeScience South Africa (Pty) Ltd. Forester® is a registered herbicide (L8891) for the control of *P. hysterophorus* in South Africa and is used by Ezemvelo KZN Wildlife (EKZNW) in protected areas. The herbicide is an irritant and must be handled with care during application. This study focuses on assessing the impact of the metsulfuron-methyl 600 g kg-' on *P. hysterophorus* and non-target species coexisting with the weed during application.

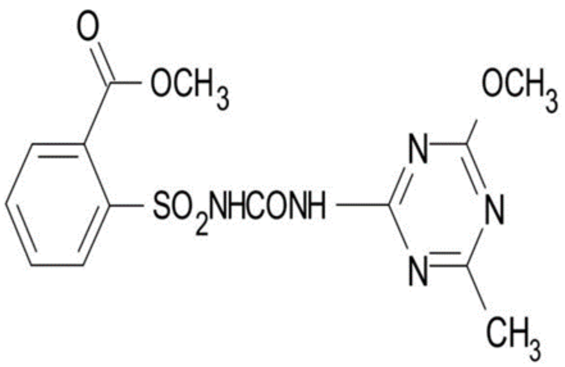

Figure 4.1: Molecular structure of the metsulfuron methyl herbicide (Abdul et al., 2009).

EKZNW is a government institution whose mandate is to preserve KwaZulu-Natal's natural resources and ensure the protection of species that are of conservation significance. It is therefore vital to assess weed control methods used by an organization committed to conserving KwaZulu-Natal's ecological integrity. Hluhluwe-Imfolozi Park (HiP) is an Ezemvelo KZN Wildlife protected area, noted by McDonald and Lee (2013) as having *P. hysterophorus* infestations. Famine weed (*Parthenium hysterophorus* L.) is now a major threat to the natural vegetation in a number of protected areas globally (Adkins and Shabbir, 2014). The Zululand (Northern KwaZulu-Natal) region is highly susceptible to the spread of *P. hysterophorus* as a result of the high rainfall in the area during 2016 (Royimani et al., 2019). With the prominent infestations of *P. hysterophorus* in the communal areas surrounding HiP, data collection was conducted both inside and outside of the reserve in order to compare levels of infestation across adjacent and contrasting land uses and the threat of further invasion from outside the park. *Parthenium hysterophorus* biomass increased notably in the year 2016, post-drought, both inside the reserve and its surroundings (Royimani et al., 2019), hence, Ezemvelo KZN Wildlife has initiated a chemical invasion control program (Ezemvelo KZN Wildlife, 2011). HiP is an immensely invaded area. At present, over sixty-three alien invasive plant species have colonized the park (Ezemvelo KZN Wildlife, 2011). The organizations commitment to execute long-term control management programs so as to minimize alien invasive species impacts on biodiversity is one of their conservation objectives outlined in the park's management plan, which also applies to the buffer areas as they significantly influence the ecological functioning of the park (Ezemvelo KZN Wildlife, 2011).

4.3 Methods and Materials

4.3.1 Description of study site

The study was conducted in the Hluhluwe Game Reserve and its buffer zone, near the Memorial Gate entrance to the reserve (Figure 4.2). The park is 90000 hectares in area (Graf et al., 2009). A corridor exists in Hluhluwe-Imfolozi Park separating the original Hluhluwe Game Reserve (24000 ha) and Imfolozi Game Reserve (72000 ha). The reserve is commonly known as Hluhluwe-Imfolozi Park, which is located at 28.2198˚S, 31.9519˚E, northeast of KwaZulu-Natal, South Africa. The park has a sub-tropical climate, characterized by wet summers and dry winter periods. The reserve receives between 390 and 1250 mm of rainfall is received per annum (Jolles, 2007), and temperatures ranges between ±13 °C during winter to ±35 °C (Ezemvelo KZN Wildlife, 2011; Jolles, 2007). Hluhluwe-Imfolozi Park is home to the endangered white and black rhino, and elephants (Cromsigt et al., 2017). The vegetation in Hluhluwe-Imfolozi Park ranges from evergreen forest and savanna grassland in the northern section to arid thornveld in the southern section (Acocks 1953; Mucina and Rutherford, 2006). Hluhluwe-Imfolozi Park falls under the Maputaland-Pondoland-Albany (MPA) hotspot of Southern Africa, an area of significant biological diversity and ecological importance (Di Minin et al., 2013). Due to a rainfall gradient from the Hluhluwe to the Imfolozi side with the Hluluwe side being wetter, *Parthenium hysterophorus* infestations in Hluhluwe are higher compared to the Imfolozi section. The high invasion rates in Hluhluwe necessitated its selection as study area for this study.

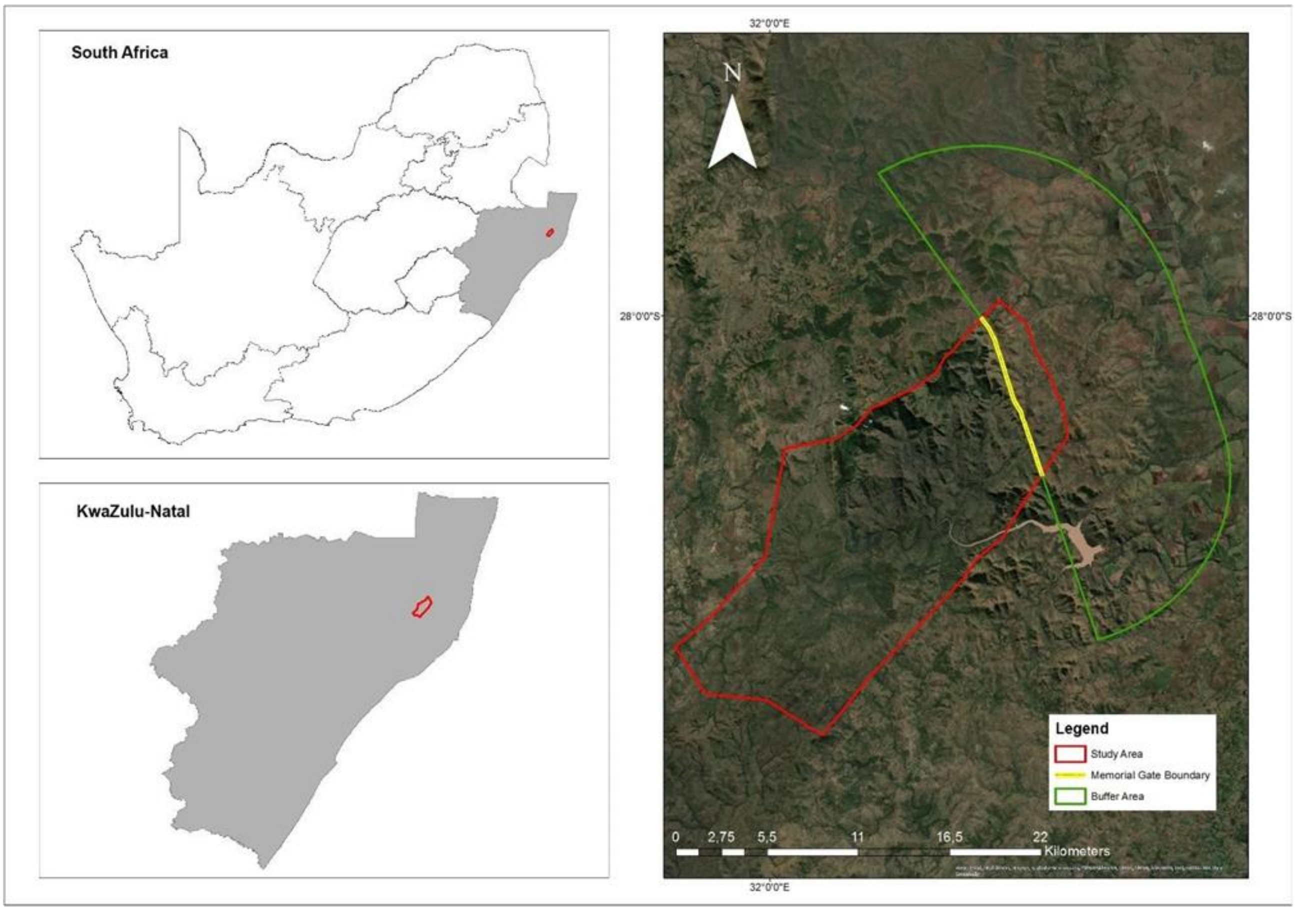

Figure 4.2: Location of the study area in the Hluhluwe Game Reserve and its 10 km Buffer Zone.

4.3.2 Field data collection

Field experiments were conducted to evaluate the impact of chemical control of *Parthenium hysterophorus* on native plant species diversity; viz. the impact of herbicides used 14 days (short-term) after treatment (DAT) and short to medium term (12 months) after treatment on non-targeted species. Herbicide application was conducted during late growth stages and post flowering i.e. late summer (March 2019 and February 2020) (Figure 4.3B). Monitoring data was collected throughout 2019 and a few weeks after herbicide application in 2020. At each sample site, the study plots were arranged in a complete randomized block design of untreated and sprayed plots, with three replicates per site (inside and outside the reserve i.e. 6 x2 = 12 plots in total) (Figure 4.3A). The plots' size per treatment viz. untreated and sprayed was 10 m x 10 m (100 m^2). In each plot, species composition data were recorded before and after spraying as counts to calculate species diversity i.e. the total number of plant species in each plot and the number of individuals per species. These values were used when computing Shannon's and Simpson's diversity index (DI) for each plot, before and after herbicide application. A total of 66 plant species (species richness) were identified in this study and were categorized as the non-targeted plant community. In plots, *P. hysterophorus* percentage cover was estimated before and after treating with metsulfuron-methyl herbicide (Goodall et al., 2010). *P. hysterophorus* infestations were sprayed with metsulfuron-methyl inside the 10 m x 10 m uncontrolled plots using a knapsack sprayer.

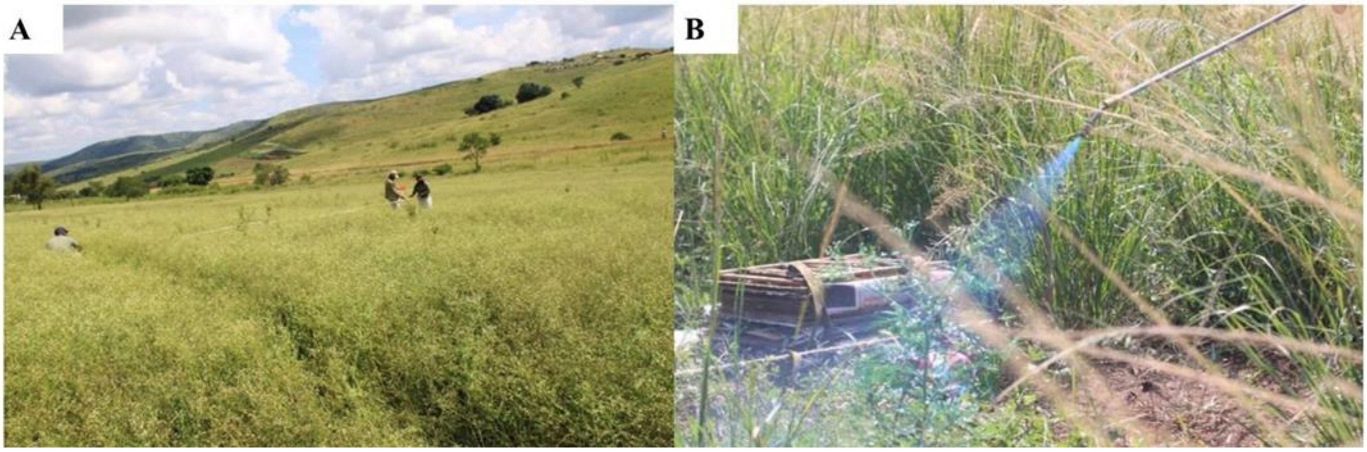

Figure 4.3: A) Setting up plots in *P. hysterophorus* infested areas. B) Applying the metsulfuron-methyl herbicide on *P. hysterophorus*.

Herbicide was applied at a rate of 15 grams dosage per 100 litres of water as recommended by the manufacturer. The effect of the herbicide on *Parthenium* and non-target species diversity was assessed from 2 to 4 months DAT. Mortality of *Parthenium* was monitored and recorded every two weeks for a period of 3 months twice a month on a scale of 0-100, where 0 equals no effect and 100 equals complete mortality. Percentage cover of resprouts and seedlings were also recorded during monitoring visits. For the short to medium term period, the exact same plots that were sprayed in 2019 were monitored for 12 months. Herbicide application in 2020 only informed the effectiveness of the herbicide for a short-term period, building up on short-term data collected in the previous year.

4.3.3 Data analysis

4.3.3.1 Shannon's diversity index

Shannon's diversity index was used to evaluate species diversity, where a high Shannon index indicates a high native species or/and weed diversity in the study area.

$$H = -\sum_{i=1}^{s} p_i \ln p_i$$

4.3.3.2 Simpson's diversity index

Simpson's index, which is a species dominance index, was calculated to measure the number of species present and their relative abundance. A reduced Simpson's diversity index will indicate high dominance of the weed.

$D = 1 - (\sum n (n - 1) / N (N - 1))$

4.3.3.3 Statistical analysis

SPSS V26 (IBM, 2019) software was used to run a regression analysis to test the relationship between species in response to the presence of *P. hysterophorus* (Timsina et al., 2011) in controlled and sprayed plots, both inside and outside of the protected area. The regression analysis shows the change in *P. hysterophorus* cover in response to the application of the metsulfuron-methyl herbicide in sprayed plots for short and short to medium time scales. In controlled plots, a regression analysis was performed to distinguish the relationship between *P. hysterophorus* and other species' dominance to deduce the significance of applying the herbicide in all *P. hysterophorus* invaded regions. The Students' t-tests analysis was performed to test the significance of differences in means for the different treatments. The test was performed to establish if sprayed and unsprayed plots, both inside and outside the protected area are statistically significantly different to each other, based on collected data.

4.4 Results

4.4.1 Efficacy of control and herbicide impact on non-targeted plant community

There was a drastic decrease in *P. hysterophorus* percentage cover after herbicide application in both the protected area and the buffer zone (Figure 4.4). *Parthenium hysterophorus* initial cover was 30% within the protected area and 86% within the buffer zone. The *P. hysterophorus* cover declined to 0% (completely dead) two weeks after spraying in both the protected area and the buffer zone. The percentage cover of the non-target or other species remained relatively constant after spraying. In the protected area, the other species cover was high at about 70% before spraying and declined by only 4% total cover, which was not significant ($p = 0.841$) . The initial cover by other species was low at 18% in the buffer zone and declined by only 2% after spraying.

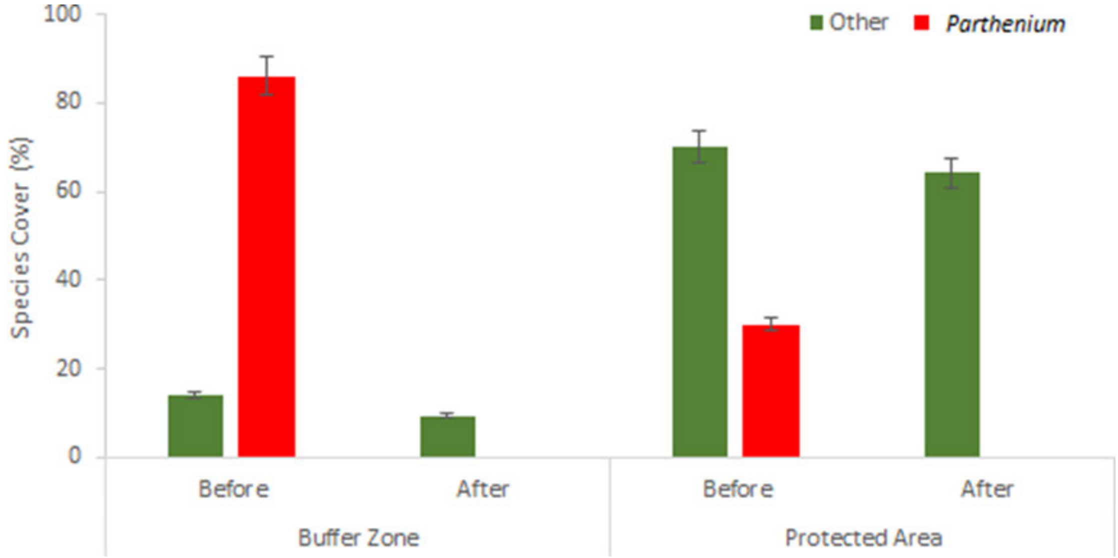

Figure 4.4: Mean total cover (± standard deviation) of *P. hysterophorus* and the non-target plant community before and after applying the metsulfuron-methyl herbicide (2 weeks) (n = 12).

Figure 4.5: 100% mortality rate of the target IAP was evident two weeks after applying metsulfuron-methyl. The figure shows a clear distinction between sprayed (dead flora in the foreground) and controlled plots.

The non-target plant community was largely unaffected by the spraying (Figure 4.5) as the recorded difference in percentage cover before and after the spray is less than 6% for both within the protected area and the buffer zone in this study. Figure 4.6 depicts the invasiveness of the *P. hysterophorus* before spraying and the survival of the non-target species after spraying.

Figure 4.6: *P. hysterophorus* mortality of the exact same quadrat, leaving the non-targeted plant community unaffected.

4.4.1.1 Short-term efficacy of control

The predicted immediate change in *P. hysterophorus* cover was estimated using the calculated difference of (after – before) spray percentage cover (Figure 4.7). The linear regression line shows a 100% mortality rate of the target weed can be expected two weeks after applying the metsulfuron-methyl herbicide. The regression equation predicts that as the initial cover increased, there was greater response from herbicide application. For a unit increase in the initial cover, the change in cover after herbicide application increase by 0.89 units. The R-square value of 0.86 denotes that the model was strong and could explain 86% of the total variation in cover change after application of herbicide over a short-term period.

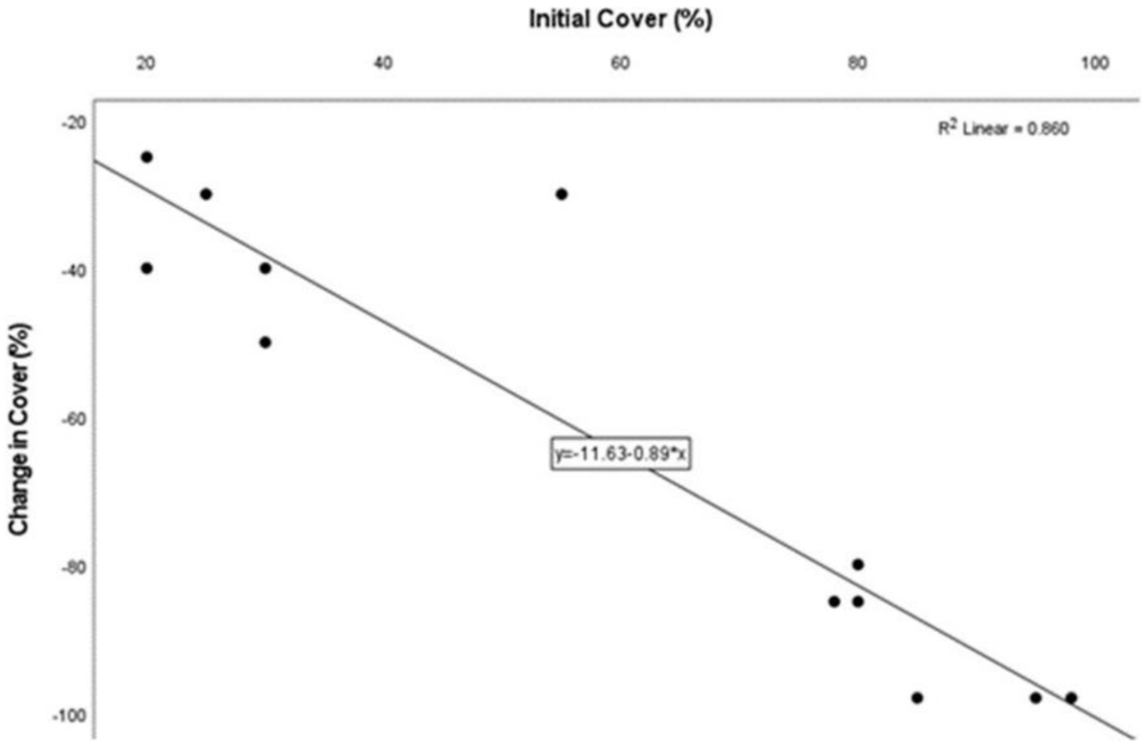

Figure 4.7: A regression analysis showing short-term (2 weeks) effects of applying the metsulfuron-methyl herbicide in *P. hysterophorus* invaded areas (n = 12).

4.4.1.2 Short to medium term efficacy of control

Figure 4.8.1 shows that there was a generally greater response to metsulfuron-methyl herbicide application in the buffer zone in the short to medium term. In the buffer zone, *P. hysterophorus* cover would be expected to decrease by 0.53 units for every unit increase in the initial cover over the short to medium term. In comparison, the *P. hysterophorus* cover would be predicted to decrease by 0.25 units in the protected area for a unit increase in the initial cover. The models for predicting response of *P. hysterophorus* cover in both the protected area and buffer zone explained 84% of the variation in cover change over the short to medium term as indicated by the R square values of 0.84. There was a smaller difference in response of other species between protected areas and buffer zones compared to the difference in response of *P. hysterophorus* cover between the protected area and buffer zone. Figure 4.8.1 shows a 1 unit increase in vegetation cover in the protected area that is associated with a 0.36 unit decrease in response, subsequently becoming greater than *P. hysterophorus*. In the buffer zone, a 1 unit increase in other species percentage cover resulted in a 0.46 unit decrease after spraying the herbicide, which indicates that other species are not as significantly affected as the *P. hysterophorus* within the protected area. The regressions for other species are stronger than for *P. hysterophorus* with R square values of 93% and 86%.

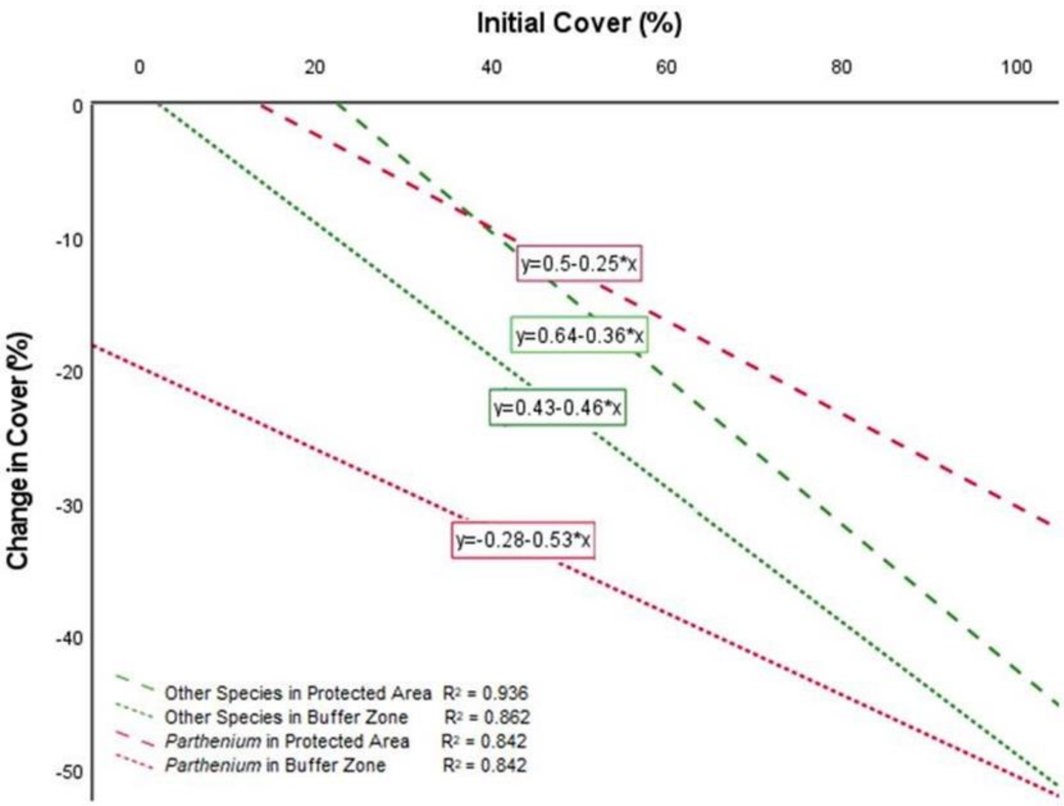

Figure 4.8.1: Short to medium term (12 months) effect of the metsulfuron-methyl herbicide on *P. hysterophorus* and the non- target plant community inside and outside the protected area.

The results in Figure 4.8.2 represent the predicted change in the cover of *P. hysterophorus* and other species in the unsprayed plots in the short to medium term. Data collected in 2019 and 2020 were used to estimate the change in percentage cover for each species class. Figure 4.8.2 shows a linear negative correlation, predicting a decrease in *P. hysterophorus* and other species even for unsprayed plots. The *P. hysterophorus* and other species cover are expected to decrease at relatively slower rates in the buffer zone, compared to the protected areas over a long period. In the protected area, the *P. hysterophorus* cover would be expected to decrease by 0.60 for every unit increase in initial cover compared to a decline of only 0.10 for non-target species. The buffer zone will lose 0.39 units in *P. hysterophorus* cover for every unit increase in the initial cover. The models for predicting response of *P. hysterophorus* cover explained 66% in the buffer zone and 81% in the protected area of the variation in cover change over a short to medium term as indicated by R square values of 0.66 and 0.81. Figure 4.8.2 shows a 1 unit increase in other species vegetation cover in the buffer zone that is associated with a 0.17 unit decrease in response. The R square values for the non-target plant community are 96% in the protected area and 89% in the buffer zone.

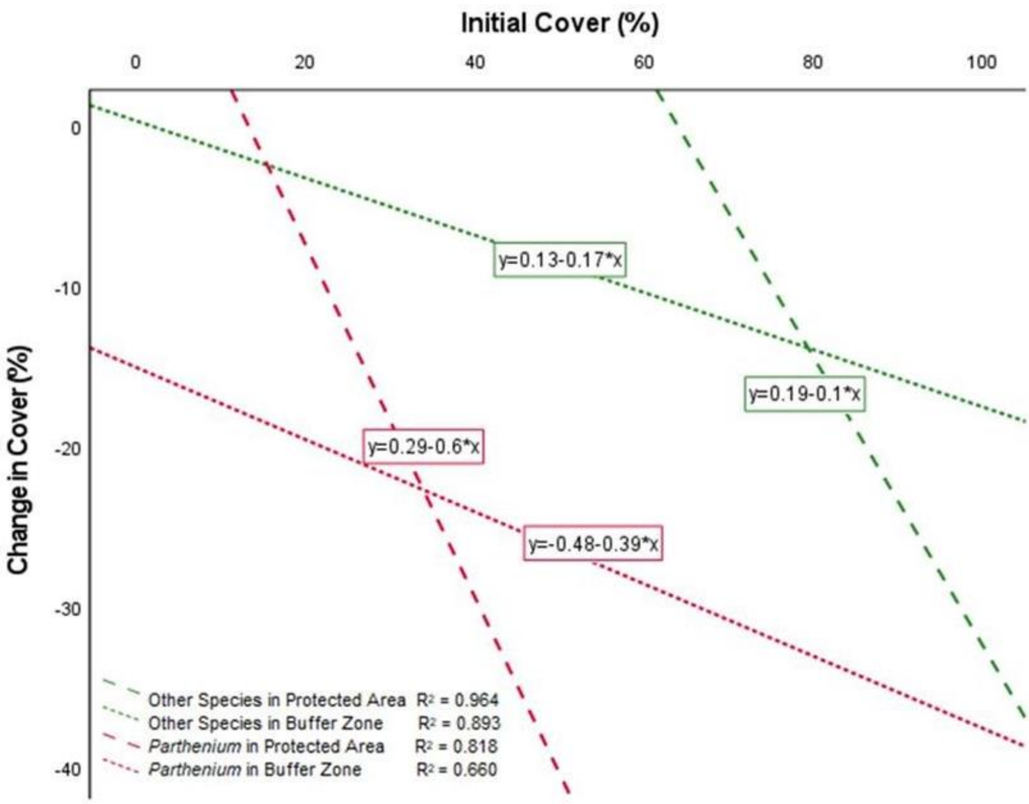

Figure 4.8.2: Short to medium term (12 months) monitoring of unsprayed areas with *P. hysterophorus* infestation.

The Shannon`s and Simpson`s indices remained the same before and after treatment in both the protected area and its buffer zone, hence there was no effect. The total vegetation cover in the protected area remained relatively similar in the sprayed and unsprayed plots over a short period of two weeks after spraying. In contrast, the species cover in the buffer zone showed a significant decline from 50% to 4.67% two weeks after spraying. The initial cover of *P. hysterophorus* was 65.83% and declined significantly after spraying to 34.17% in the protected area. In the buffer zone, both initial cover and percentage change in cover showed significant differences between sprayed and unsprayed plots (t= 11.27, df= 10, p <0.001). The percentage decline in *P. hysterophorus* cover was 40.43% after spraying compared to only a 3.3% decline in the control plots in the buffer zone.

Table 4.1 T-tests analysis to test the significance of differences in means of cover (%) and DI (diversity index) for the different treatments i.e. sprayed and unsprayed plots, both inside and outside the protected area.

		Short-term (2 weeks)						Short to medium term (12 months)	
Category	Treatment	% Cover of all Species Before spray	% Cover of all Species After Two Weeks	Simpsons DI (Before)	Simpsons DI (After)	Shannon's DI (Before)	Shannon's DI (After)	% Initial Cover of all Species	% Change in Cover of all Species
Protected Area	Control	50.00	50.00	0.7620	0.7620	1.5514	1.5514	65.83	-13.83
	Sprayed	50.00	32.08	0.7166	0.7166	1.5560	1.5560	34.17	-13.00
	Std. Error Mean	7.017	7.017	0.0619	0.0619	0.14981	0.14981	3.745	3.458
	t value	0.000	1.483	0.648	0.648	-0.022	-0.022	5.98	-0.21
	df	22	22	10	10	10	10	10	10
	P	**1.000**	**0.152**	**0.532**	**0.532**	**0.983**	**0.983**	**<0.001**	**0.841**
Buffer Zone	Control	50.00	50.00	0.6123	0.6123	1.2618	1.2618	12.67	-3.33
	Sprayed	50.00	4.67	0.6422	0.6422	1.3483	1.3483	87.33	-40.83
	Std. Error Mean	11.104	11.104	0.06002	0.06002	0.19851	0.19851	3.556	1.256
	t value	0.000	4.009	-0.191	-0.191	-0.232	-0.232	-14.85	11.27
	df	22	22	10	10	10	10	10	10
	P	**1.000**	**0.001**	**0.852**	**0.852**	**0.821**	**0.821**	**<0.001**	**<0.001**

4.5 Discussion

This study aimed to examine the short and short to medium term herbicidal efficacy in controlling *P. hysterophorus* in one of Ezemvelo KZN Wildlife's protected areas, Hluhluwe-Imfolozi Park and its peripheral area. Establishing both the short and short to medium term effects of applying the metsulfuron-methyl herbicide in controlling *P. hysterophorus* is essential for devising appropriate management strategies for effective results. The study found minimal impact of metsulfuron-methyl on non-target species. This is important to ensure sustainable maintenance of native species during control of invasive species. A previous study by Ramdu et al., (2020) also reported that herbicidal control barely impacted on other plant species. Ramdu et al., (2020) further asserted that chemically controlling exotic plants for mid/long-term results is effective as it minimizes the development of sprouts or the sudden appearance of the exotic species but mechanical control methods should also be used to complement herbicidal efficacy in the short to medium term. For short-term results, this study found a 100% mortality rate of *P. hysterophorus* change in cover. Short to medium term results, on the other hand, revealed minimal changes of other species percentage cover. The metsulfuron-methyl herbicide was applied the previous year (2019) and *P. hysterophorus* initial percentage cover before spraying was 40% and decreased by 9.5% inside the protected area and 20.92% in the buffer zone, a year after spraying. Alternatively, other plant species that were initially recorded as 40% before the application of the metsulfuron-methyl herbicide were reduced by 13.76% inside the protected area and 17.97% in the buffer zone, a year after spraying (2020). A similar trend was observed for the sprayed plots where both the target weed and coexisting plant species were decreasing in percentage cover. This may be attributed to the drying out of *P. hysterophorus* and other vegetation during winter months, with or without the application of the herbicide. Summer rainfall, amongst many other seasonal variation factors that can influence plant biodiversity, can give rise to the re-emergence of many plant species post-winter months. Short to medium term variations within the unsprayed plot plant communities can be attributed to environmental conditions and anthropogenic factors, such as erosion, other than herbicide control.

4.6 Conclusions

Metsulfuron-methyl exhibited high efficacy in the short term suitable for the current management strategies being implemented by Ezemvelo KZN Wildlife in chemically controlling *P. hysterophorus*, a problematic weed in their protected areas and their buffer zones.

This study, therefore, recommends the use of the metsulfuron-methyl herbicide in controlling *P. hysterophorus*, especially since it does not affect the non-target plant community. The calculated plant species diversity indices did not change after the application of the herbicide, which is advantageous for maintaining the ecological integrity of the park and its surrounding communities. The exploration of other scientific methods in measuring the influence of external factors on species composition are recommended for future research.
In observing the short to medium term changes in *P. hysterophorus* percentage cover, this study concurs with previous studies that in order to achieve maximal results in controlling *P. hysterophorus*, both chemical control and veld management methods should be explored by Ezemvelo KZN Wildlife, or preferably, repeat spraying.

4.7 Acknowledgements

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4.8 Supplementary material

Figure 4.9 Monitoring the short to medium term influence of the metsulfuron-methyl herbicide on *P. hysterophorus* after application.

4.9 References

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CHAPTER 5

Conclusions and recommendations for further research

5.1 Introduction

As established in previous studies (Gallo and Waitt, 2011; Kohli et al., 2004 and Vitousek et al., 1996), vast levels of biological invasions at global and local scales have been shown in this study (Chapter 3). Biological invasions pose significant threats to natural environments and human benefits from healthy ecosystems (Van Wilgen et al., 2020), and their socio-economic and ecological effects are well understood and published in the literature (Rouget et al., 2004). Substantial areas of land in South Africa have been anthropogenically-altered and are dominated by invasive, rather than indigenous species (Richardson et al., 2003) and this is evident in the third chapter of this dissertation. As a result, South Africa is noted to be amongst the top developers of exceptional IAP management strategies (Rouget et al., 2004). Chapter 4 of this dissertation evaluated and addressed the need for effective weed management initiatives that do not harm the non-targeted native flora. In order to maintain the ecosystem functioning of protected and communal areas, national policies on controlling IAPs must be implemented efficiently and to effectively avoid further invasions.

5.2 Aims and objectives

The main aim of this study was to spatially evaluate *P. hysterophorus* infestation levels in the buffer zone of Hluhluwe-Imfolozi Park and assess the efficacy of current management strategies used by Ezemvelo KZN Wildlife in controlling *P. hysterophorus* and the impact of herbicide on non-target coexisting plant species. With the use of Sentinel 2 MSI remotely sensed data on the GEE platform, a one-class support vector machine classification algorithm was performed with a) spectral bands b) computed vegetation indices and c) a combination of both spectral bands and computed vegetation indices, to achieve research objectives of the study in mapping the variability of *P. hysterophorus* within the study area. Chapter 3 of this dissertation presented a *P. hysterophorus* spatial gradient of infestation with satisfactory mapping accuracies, which inform management for the development of mitigation strategies. An appropriate mitigation measure of the *P. hysterophorus* weed (Chapter 4) is the application of the metsulfuron-methyl herbicide, followed by regular execution of veld management strategies.

5.3 Challenges

5.3.1 Socio-economic and ecological impacts

In view of the abovementioned effects of *P. hysterophorus* invasion and observing its substantial spatial extent outside a protected area, it has become critical for EKZNW to allocate additional funds to a strict buffer zone management programme in controlling *P. hysterophorus.* Amongst many other socio-economic impacts, the extant infestation of IAPs has an unpleasant consequence in livestock production as it has caused an R340 million loss in profit on a national scale (O'Connor and van Wilgen, 2020). More specifically, the *Parthenium* weed is noted by O'Connor and van Wilgen (2020) to have exponentially increased its rangeland dominance by 671% as from 2006 to 2016, which has had a strong effect on the reduction of grass species percentage cover (which is also confirmed in Chapter 3 of this study). Due to the reduction of grass species, it becomes very challenging for livestock to survive (O'Connor and van Wilgen, 2020). The natural plant communities in the *P. hysterophorus* invaded regions, both inside and outside the protected area, support a wide range of domestic and indigenous mammalian herbivores. The ecological integrity of Hluhluwe-Imfolozi Park should be maintained, notwithstanding financial constraints.

5.4 Conclusions and recommendations

Following the introduction of exceptional, freely available, and user-friendly remote sensing applications in understanding invasion patterns in natural communities, it is recommended for emerging research scientists in ecology to further tackle invasion biology studies at a local scale. Frequently, management allocates IAP eradication and control funds not having the benefit of understanding the exact threat of encroachment (Rouget et al, 2004). This is, normally, due to the inaccessibility of certain rangeland areas, whereas, remotely sensed data is ideal for non-physical vegetation mapping. Localized extirpation and control projects would therefore fail to achieve optimal results in an attempt to ecologically restore natural communities. IAPs that are left untreated, in theory, may potentially continue to expand in existence. Furthermore, it is recommended that the short and short-medium term influence of different control methods, for other IAPs, other than *P. hysterophorus*, are monitored and reported. In conclusion, this study suggests an interdisciplinary approach in combating the spread of IAPs in KwaZulu-Natal, i.e. remote sensing and ecological approaches.

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APPENDIX A

Study Species (*Parthenium hysterophorus*)