Multi-date remote sensing assessment of invasive Lantana Camara species Distribution in semi-arid savanna rangelands of South Africa

BY

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Abstract

Invasive alien species pose a massive threat to biodiversity globally. A comprehensive analysis of the spatial distribution of invasive species, like *Lantana camara,* is essential for providing appropriate management strategies on both a local and regional scale. The main aim of the study was to map and assess the spatial distribution of *Lantana camara* invasion in savanna rangeland ecosystems over time in Agincourt, South Africa, using high-resolution SPOT 6 data. The first objective of the study is to focus on reviewing the progress in the remote sensing of *Lantana camara*. A review of the literature shows that previous studies on mapping and monitoring invasive *Lantana camara* have relied on traditional methods, such as visual interpretations and field surveys, which have been insufficient, particularly for large-scale monitoring. The use of commercial satellite data with a high-resolution has demonstrated the potential for providing fine spectral and spatial resolution capabilities that are essential for offering precise and reliable data on the spatial distribution of invasive species. The challenges encountered in remote sensing of *Lantana camara* include the problem of similarity in the spectral signatures of the weed and other vegetation species, which leads to a low classification accuracy. The second objective was to map the spatial distribution and rate of change of *Lantana camara* in savanna ecosystems over time and space. To achieve this objective, a supervised maximum likelihood classification was used for the SPOT 6 satellite images acquired over a period of three years (2014, 2016 and 2018). The results showed that, *Lantana camara* was distributed over almost the whole study area for all the three years, yet it decreased with time, due to the clearing and disaster programs. Furthermore, the weed then increased and re-established itself between 2016 and 2018, due to failure to do follow-up control after the initial attempts to eradicate it and the failure to remove rootstock. It was again observed that *Lantana camara* species can be accurately detected and mapped with an overall classification accuracy of >80% for all the three years. However, research with the enhanced spatial and spectral capabilities such as SPOT 6, has shown the importance of remotely sensed data in predicting *lantana camara* distribution

Key words: Clearing; ecological threats; grazing resources; livelihoods; regeneration; remote sensing; spatial distribution.

Preface

This study was conducted in the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa, from March 2018 to November 2019, under the supervision of Prof. Onisimo Mutanga and Prof. Timothy Dube in the fulfilment of the requirements for the degree of Masters' Science.

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

Ngwanamapotu Paschaline Madileng Signed ……Date…10/April 2020………………….

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

1. Prof. Onisimo Mutanga Signed… Date…4 Aug 2020..

2. Prof. Timothy Dube signed… …. Date…4 Aug 2020...

Plagiarism Declaration

I, Ngwanamapotu Paschaline Madileng, declare that:

a) the research reported in this dissertation, except where stated otherwise is my original work,
b) this dissertation has not been submitted for any degree or examination at any institution,
c) this dissertation does not contain any data, graphics, and other information from other persons, unless specifically acknowledged to be sourced from the person,
d) this dissertation does not contain any other persons' writing, unless otherwise acknowledged as such. In cases where written sources have been cited,
    i. their words have been paraphrased and general information attributed to them have been attributed to them has been referenced,
    ii. where their exact words have been utilized, they were placed inside quotation marks and referenced, and
e) this dissertation does not contain text, graphics, and tables directly copied and pasted from the internet, unless otherwise sources were duly acknowledged within the content of this dissertation.

Dedication

This dissertation is dedicated to my beloved family, for their unconditional love, as well as their endless prayers and support. I would like to thank them for trusting me to achieve this wok.

Acknowledgements

To God alone be the glory, for giving me the opportunity to study for a Masters' degree and for giving me the strength to get through the difficulty and hard times while doing so.

My sincere gratitude to the School of Agriculture, Earth and Environmental Science through the University of KwaZulu-Natal for granting me the opportunity to pursue my studies. I would especially extend my gratitude to the South African Research Chairs Initiative (SARChl), and National Research Foundation (NRF) for their financial support to pursue my studies, this study would not have been possible without the opportunity that was given to me.

My deep appreciation goes to my supervisors, Prof. Onisimo Mutanga and Prof. Timothy Dube, who sacrificed their time to help me. I am thankful for their moral support, guidance, critical comments and mentorship, which aided me to write well. I cannot thank you both enough for believing in me, no matter how stubborn and difficult I was at times. I am extremely lucky to be under your supervision; your patience meant everything to me and may the almighty God bless you abundantly.

My special thanks to the staff of the Department of Geography at the University of KwaZulu-Natal, especially Brice Gijsbertsen, and Dr. Mbulisi Sibanda, for their assistance. To my friends and colleagues, Xivutiso, Israel, Samuel, Trylee, Svuyisiwe, Renate and Nqobile, thank you for your support and your comforting words when things where tough, thanks as well as for your sweet and tough love.

My heartfelt gratitude to my family: my Mom, dad and grandmother, second mom and siblings thank you for your constant prayers and believing in me. Mahapa, thank you for encouraging me and for believing in me when I was at my worst.

God bless you all.

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CHAPTER ONE: GENERAL INTRODUCTION

1.1 Introduction

Invasive species pose a socio-economic and ecological threat that affects wildlife, livestock and agriculture globally (Brunel et al. 2013). Invasive alien species are those that have been moved from their indigenous habitat, to a new habitat (Colautti et al. 2004). Once established, these species can spread across large areas at a rapid rate (Richardson et al. 2004). Replacing indigenous species can be detrimental to herbivores, and it can lead to significant consequences for the entire community that has been invaded. Invasive alien plants are a problem of global significance, as they incur costs that run into billions of dollars annually (Cusack et al. 2009). Plant invasions present an exceptional risk to biodiversity, which is currently being undermined by habitat destruction due to human population growth (Pejchar and Mooney 2010). At least 161 exotic species were introduced in South Africa mostly as ornamental flowers and for medicinal purposes. These species cause serious problems for both natural and semi-natural systems (Henderson 2004), impacting on 10 million hectares (8%) of the country's land area (le Maitre et al. 2000).

Lantana camara is one of the major invasive alien plants, which is distributed all over the world and has spread from its native central and South America to about fifty different countries, including Zimbabwe, India, Australia and South Africa (Priyanka and Josh 2013). The species is mostly introduced into a region through human activities such as ornamental flowers and for medicinal purposes (Simberloff et al. 2016). The introduction of *Lantana camara* to an environment leads to a severe risk to the biodiversity, rangeland and forestry. An increase in trans-boundary movement, as well as global economic trade, makes it almost difficult to ignore the spread of this alien invasive species across countries (Arriaga et al. 2004). The major challenge with these species is that they can quickly eliminate native species through competition and the disruption of ecosystem functions (Arriaga et al. 2004). It reduces the economic sustainability of the crops, causes the loss of pasture in grazing areas and provide a habitat for plant pests and diseases (Chatanga 2007). According to Thekaekara (2015), the seeds have been found to be poisonous when ingested and can increase livestock and wildlife mortality rates.

Environmental managers have recognized the need for effective control programs to counter the impacts and to clear the environment of invasive alien species (*Lantana camara*) (Holling et al. 1978), and many efforts have been made to come up with such programs globally. Some programs have been relatively successful, but many of them have failed (Zachariades 1999). The integrated control of invasive alien plants has been trying their best to make the clearing programmer a success, hence, it has not been guaranteed the programmer will be easy. For instance, in the South African government, through the Department of Water and Sanitation (DWS) and Department of Agriculture Forestry and Fisheries (DAFF), has introduced the Working for Water program that focuses on the clearing of invasive species. Although this has been viewed positively, the knowledge about the influence of these endeavors on the restoration of ecosystems remains rudimentary. It is well known that the introduction of *Lantana camara* negatively affects vegetation cover by reducing soil nutrients, and texture, since the specie can release toxic chemicals that disturbs native. Therefore, the clearance of this noxious species gives the native species a chance to regrow, thus leading to recovery of soil nutrients and biodiversity growth (Hoddle 2004).

Despite the dreadful effects of *Lantana camara* on the environment, the rate at which *Lantana camara* is spreading into new environments has been poorly documented. Most of the available statistics to date have been dependent on visual interpretations. In measuring the magnitude of change in *Lantana camara* spatial distribution sustained surveys have been restricted to small areas and requires additional data for analysis. For example, Pakeman and Marrs (1996), conducted a study using field surveys and visual interpretations to quantify landscapes that could be possibly invaded by invasive plants and to identify the major areas where global climate change increases the prevalence of alien weeds. However, no results were presented in terms of the rate at which *Lantana camara* invades a new landscape, hence, its distribution patterns remain unknown for that period.

More recently, remote sensing has appeared to be a dependable technique for vegetation mapping and monitoring (Bégué 2019). Remote sensing technologies proved to be useful in mapping and monitoring invasive species overtime. Previous studies used medium spatial resolution satellite imagery for mapping the spatial distribution of *Lantana camara*. For example, Taylor et al. (2011) compared the accuracy results for mapping *Lantana camara,* using QuickBird, Landsat TM and SPOT 5, and to evaluate the cost- effectiveness of the images. The use of medium spatial resolution images in the detection and mapping of *Lantana camara* has been constrained by their inadequate spatial and spectral capabilities and the high cost of imagery. Although multispectral remote sensing has the capability of detecting and mapping alien plants, the weeds are often unnoticed in a backdrop of natural vegetation, making them difficult to detect (Mundt et al. 2005). Remote sensing of intrusive plants has been extensively applied in mapping the distribution of invasive species in aquatic, wetland, riparian, prairie or desert areas, where the limited presence of tree cover gives the sensors an unmistakable perspective of the invasive plants (Amri et al. 2009). The use of remote sensing has proved to be a reliable source of environmental data and has become common in ecological research, supplying an accurate and equitable method for obtaining data over large areas.

High spatial resolution satellite imagery such as SPOT 6 has been anticipated to provide the most required essential data sources necessary for repeated monitoring of small and enormous vegetation areas (Thamaga and Dube, 2018). Khare et al. (2019) showed that SPOT 6 sensor consist of a panchromatic band with a 1.5m resolution making the image to be more visible, and it can discern earth's vegetation species with high accuracy, which can further enhance the detection and mapping abilities of the sensor. Other related studies demonstrated their successful applications and performances in invasive species monitoring (Wang et al., 2015; Alvarez-Taboada et al. 2017), land-use and land-cover mapping (Zylshal et al. 2015; Akay and Sertel, 2015) and soil erosion mapping (Phinzi and Ngetar 2017; Sepuru and Dube 2018). The introduction of new generation sensors i.e. SPOT 6, with its improved image acquisition and sensing characteristics, is therefore, anticipated to provide innovative opportunities for the mapping and monitoring of the spread and distribution of invasive *Lantana camara* species, at both a local and regional scale. Therefore, this study sought to map the spatial distribution of *Lantana camara* invasion in savanna rangeland ecosystems overtime using high-resolution SPOT 6 data.

1.2 Aim

The overall aim of the study was to map the spatial distribution of *Lantana camara* invasion in savanna rangeland ecosystems overtime using high-resolution SPOT 6 data

1.3 Objectives

- To review the progress and challenges in mapping *Lantana Camara* weeds using multi-spectral remotely sensed data.
- To map the spatial distribution and rate of change of *Lantana camara* in savanna ecosystems over time and space.

1.4 Research questions

- Does the multispectral SPOT 6 sensor successfully detect and map *Lantana camara*?
- Does the spread and spatial distribution of *Lantana camara* vary overtime?

1.5 Main hypothesis

- The new generation SPOT 6 sensor, with its unique sensor characteristics, such as its high-resolution and revisit time, can effectively detect and map the spread and spatial distribution of *Lantana camara.*

1.6 Description of study area

The study was conducted in Agincourt of the Mpumalanga Province, South Africa (Figure 1.1), which is in the previous Gazankulu and Lebowa regions and which covers an area of 2417 km^2. The region lies between - 24.82789 latitude and 31.21971 longitudes, and it is situated between the Drakensberg escarpment in the west, Kruger National Park and Sabie-Sand Game Reserve in the east (Tollman 2009). There is a solid inclination of diminishing precipitation over the area from 1200 mm per annum in the west against the Drakensburg escarpment to 500 mm per annum in the East. The mean annual temperature is roughly 22˚C, and frost is uncommon (Govere et al. 2000). The landscape is level to undulating and the broadest soil types are thin sandy lithosols, except for those towards the base of the incline, where more profound duplex soils are normal (Giannecchini et al. 2007). The regular vegetation in the region is open, deciduous forest and extensive grasslands. Dominating livestock in this area are mostly cattle and goats. Agricultural activities in this region are mostly crop planting (Shackleton et al. 2002). Typically, the Agincourt field sites show terrain covered by *Lantana camara*, appearance of *Lantana camara* during summer times, terrain covered by trees, shrubs and grass and wildlife grazing in area invaded by *Lantana camara* (figure 2.2).

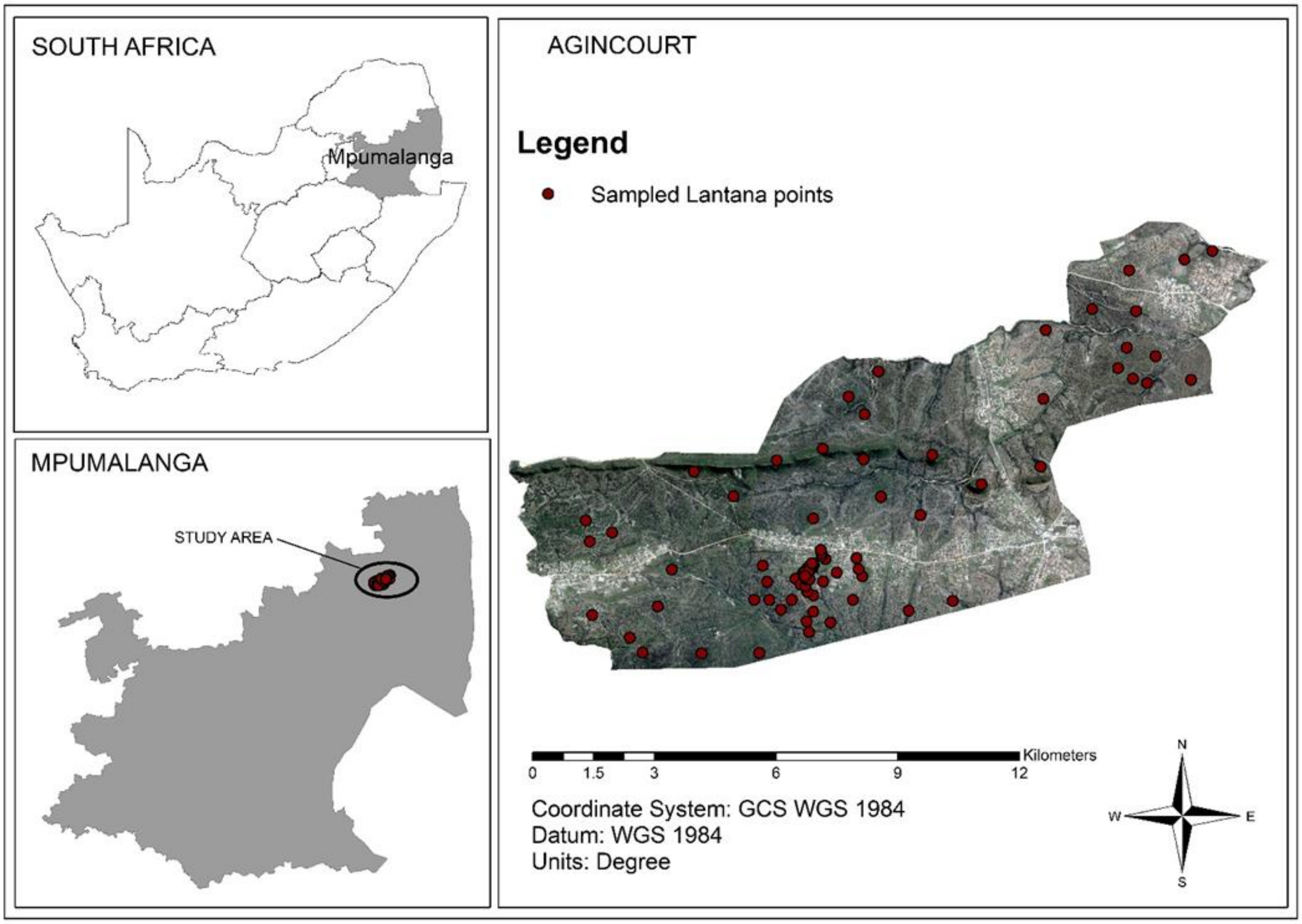

Figure 1.1: Map of study area

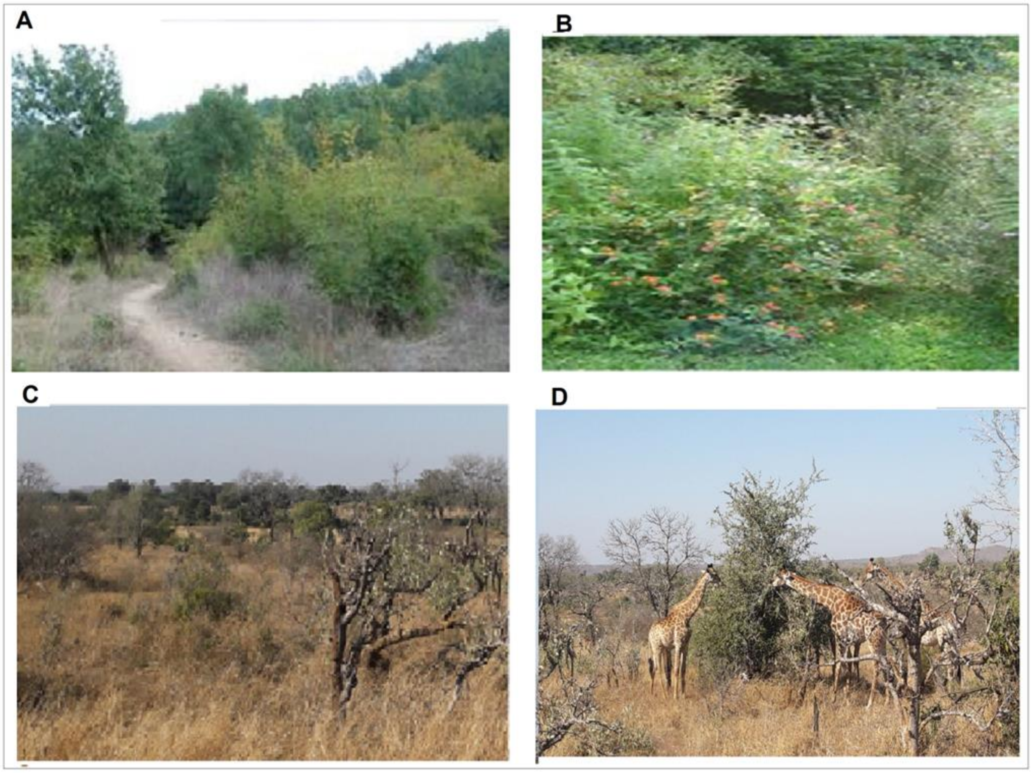

Figure 1.2: Typically, the Agincourt field sites show (A) terrain covered by Lantana camara, (B) appearance of Lantana camara during summer times, (C) terrain covered by trees, shrubs and grass and (D) wildlife grazing in area invaded by *Lantana camara*

1.7 General structure of the thesis

This dissertation consists of four chapters including general introduction and synthesis chapters. Consequently, the methodology and literature review are contained within the following chapters.

CHAPTER ONE: In this chapter, the general overview and research background are provided, together with outlined objectives and the general structure of the thesis.

CHAPTER TWO: This chapter highlights the progress made in mapping the spatial distribution of *Lantana camara*, together with tracing changes made after clearing of this weed using high-resolution SPOT 6 data. The study further highlights the predictive techniques that have been used to map the distribution of *Lantana camara*, and the directions for using high-resolution sensors in future to detect and map the weed in environments.

CHAPTER THREE: In this chapter the newly launched remote sensing satellite imagery (SPOT 6) is tested and the spatial distribution of *Lantana camara* amongst other land cover types is mapped over a period of three years. The study then compared results for all the three years (2014, 2016 and 2018). It shows that SPOT 6, with its high-resolution, is capable of mapping *Lantana camara* over-time.

CHAPTER FOUR: This chapter provides a synthesis of the research findings, as well as the discussions and conclusions of all the chapters. Consequently, this section revisits and provides an evaluation of each research objective. Thereafter, recommendations for future research discussed.

CHAPTER 2: MAPPING AND MONITORING *LANTANA CAMARA* USING REMOTE SENSING APPLICATIONS: A REVIEW

Abstract

Invasive alien species, such as *Lantana camara*, contribute immensely to environmental degradation and the loss of biodiversity. The literature indicates that *Lantana camara* poses a threat to ecological and socio-economic systems by inhabiting agricultural areas, as well as natural ecosystems. Environmental reports, including field surveys, reveal that *Lantana camara* has poisonous seeds and increases the mortality rate if it is ingested by livestock and wildlife. This invasive weed further affects the functionality of the environment and the productivity of crops negatively, due to its high consumption of water, as well as the release of toxic chemicals, which destroy native plants. The *Lantana camara* species also can survive under any harsh and intolerant circumstances, such as droughts, floods and high temperatures. Hence, the review highlights the progress done so far to understand the spatial distribution of *Lantana camara*, the application of techniques for its eradication as well as the successes recorded using remote sensing applications. Previous studies on mapping and monitoring invasive species relied on traditional methods for instance, visual interpretations and field surveys and these were considered inadequate, particularly for large scale monitoring. High-resolution satellite data have shown potential for providing fine spectral and spatial resolution abilities, which are fundamental for offering precise and solid information on the spatial distribution of intrusive weeds. Remote sensing applications provide a good alternative for mapping invasive *Lantana camara* species, hence they have gained substantial momentum in the last decades globally. Satellite SPOT 6 images consist of high-resolution and improved sensing characteristics, which can enhance the detection, mapping and monitoring of this harmful species. Thus, the latest developments in remote sensing technology and the availability of these data in various resolutions, as well as the demand for instant and improved progress information on detecting, mapping and modelling of *Lantana camara* has received substantial attention.

Keywords: ecosystem, invasive species, environmental degradation, and, ecological systems.

2.1 Introduction

Lantana camara is a shrub with multi-colored flower clusters and dark-green hairy leaves with re-curved thorns (Sultana 2016), see figure 2.1. Different species are influenced by this weed as it releases an assortment of chemicals and vital oils from its leaves, which can be harmful if it is consumed by livestock and wildlife, as it causes infertility and increases mortality (Sharma 1988). According to Chatanga (2007), *Lantana camara* has been ranked amongst the top-hundred global invaders. The invasion of this weed has caused a serious deterioration in the quality and quantity of the available land used for grazing, which has resulted in forage shortages (Kohli et al. 2006). Literature shows that the weed has become a major intruder in agriculture as well as natural ecosystems resulting in a significant decrease in thickness and biomass of the indigenous plant (Grice 2006). Environmental studies have revealed that *Lantana camara* can reduce the richness of species overpowering the restoration of the indigenous tree population. For example, its intrusion in the Sandalwood forest, India has negatively influenced the development of trees and has favored the increase of the sandal spike disease (Muniappan and Viraktamath 2008). Prasad (2009) further revealed that, *Lantana camara* also cause forest resource exploitation in Western Ghats, which includes the exploitation of fuel wood harvest and livestock grazing. *Lantana camara* has a massive negative economic impact if it targets commercial crop species (IUCN 2000), or indirectly influences them; for example, by destabilizing the soil, which can cause extinction, modify ecosystem processes and act as disease vector, affecting both humans and animal species (Shoko et al. 2016)

Observed evidence from literature revealed that the spatial distribution of *Lantana camara* cannot be accurately mapped using traditional methods such as field surveys and visual interpretations (Dowling and Accad 2003). These methods have been restricted to small areas and did not produce accurate results because they required experience, they are also time-consuming, laborious and costly (Ward and Morgan 2014). Available remote sensing techniques were used in numerous research projects to detect, map and monitor the distribution of *Lantana camara* at different scales. Previous studies in mapping the spatial distribution of *Lantana camara* used medium spatial resolution satellite imagery; for example, Dhau (2008), who used Landsat TM and Aster to map and monitor *Lantana camara* invasion in three land tenure systems in Zimbabwe. Kimothi and Dasari, (2010) investigated the “methodology to map the spread of an invasive plant (*Lantana camara*) in forest ecosystems using Indian remote sensing satellite data” also demonstrating the potential of Linear Imaging Self-Scanning Sensor Cartosat-

1 and” (LISS) IV data for detecting of “*Lantana camara*. Taylor et al (2011) compared the accuracy results for mapping *Lantana camara* using QuickBird, Landsat TM and SPOT 5 as well as evaluating the cost-effectiveness of the images. This study reviews the remote sensing applications for the mapping and monitoring of *Lantana Camara*. The study identifies the spectral characteristics of *Lantana camara* and highlights then potential of remote sensing, citing relevant literature.

The study then focuses on the potential and progress faced in the remote sensing of *Lantana camara*, as well as available techniques used to map the weeds at different scales. Specifically, the research paper focuses on the following: (i) a concise summary of the global distribution of *Lantana camara,* (ii) highlights the role of mapping *Lantana camara* using remote sensing, together with the” trade-offs between satellite mapping accuracy and image acquisition costs. The suitable temporal, spectral and spatial resolutions that are good for mapping *Lantana camara* are discussed. Furthermore, (iii) this review discuss the techniques that are used to classify *Lantana camara* using remotely sensed data, focusing on image pre-processing, field data collection methods, validation procedures and “classification algorithms are also included. A comprehensive summary on different algorithms and methods available, together with future” research directions in mapping and monitoring “the invasive species is also highlighted.”

Figure 2.1: Characteristics of *Lantana camara* photograph, source: Ghisalberti (2000)

2.2 Literature search

To accomplish objectives, the applicable information was obtained from Earth Observation, GIS and Remote sensing journals. Throughout literature search, international peer-reviewed journal articles published by the Institute for Scientific Information (ISI) were selected. Familiar search engines, for instance, Google Scholar and the ISI Web of Knowledge database, as well as, other international remote sensing and invasive species journals, were utilized to select the appropriate journal articles.

2.3 Global distribution of *Lantana camara*

Lantana camara is mostly found in open spaces and un-shaded conditions where it basically substituted most native vegetation in agricultural areas, grasslands, wastelands, beachfronts, wetlands, the edge of rainforest and forests recovering from fire or logging. Furthermore, logging worsens the circumstances and allows *Lantana camara* to become thicker in its growth figure 2.1, therefore obstructing forest operations (Ghisalberti 2000). Tropical and subtropical regions are mostly predicted to have appropriate climatic conditions that favors *Lantana camara* (Baars et al. 1999). For example, vast ranges of South and Central America have profoundly reasonable climate for this species. Warm mild regions including Southern Mediterranean, Europe, and Northern New Zealand (figure 2.2) are anticipated to have unsatisfactory climates (Goncalves et al. 2014).

However, in the eastern parts of Africa including Tanzania, Rwanda, Kenya Uganda and Ethiopia, *Lantana camara* is mostly distributed along riverbanks and roads. It has been found that forage available to livestock have been decreased by more than 50% (Shackleton et al. 2017). Whereas *Lantana camara* in South Africa is present mostly in temperate, moist subtropical and warm regions (Baars and Neser 1999), which includes Eastern Cape, Mpumalanga, KwaZulu-Natal, Limpopo, Western Cape, and Gauteng, but it dominates mostly in KwaZulu-Natal. A few approaches have been identified for detecting the spatial distribution of *Lantana camara*, including the predictive techniques in remote sensing (Samarajeewa 2013).

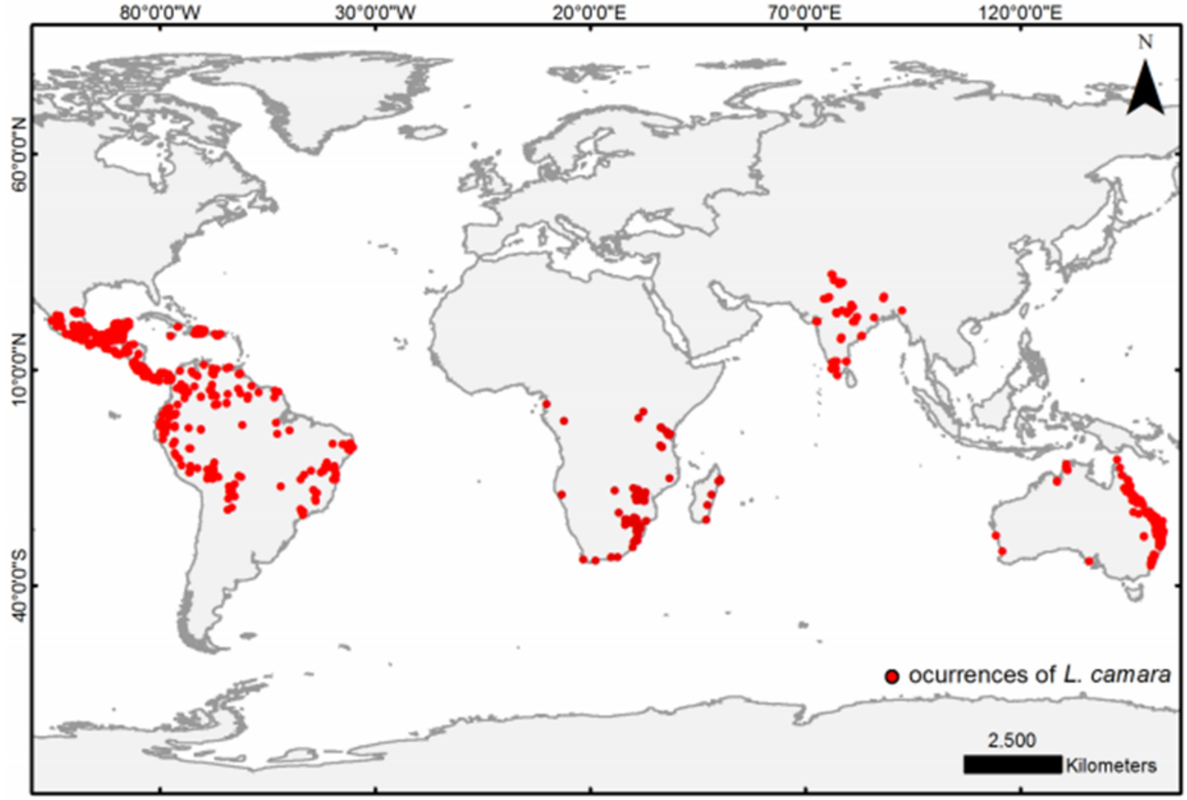

Figure 2.2: The global distribution of *Lantana camara*, source: Goncalves et al (2014)

2.4 Spectral characteristics of *Lantana camara*

Plant species have unique properties that determine their spectral reflectance, including their light-absorbing pigments, structural biochemical molecules, chlorophyll and water (Kokaly et al. 2003; Price 1992). Vegetation species such as *Lantana camara* reflect and transmit massively mainly in the near-infrared (NIR) region. Spectral reflectance curve of *Lantana camara* is presented in Figure 2.3. A Study by Taylor (1993) shows that, the field reflectance measurements of *Lantana camara* are statistically different from those of other vegetation. Furthermore, Chowdhury and Schneider (2004) revealed that the areas mostly dominated by *Lantana camara* have a high spectral reflectance, compared to landscapes with both *Lantana camara* and other vegetation species. The results from literature demonstrated that *Lantana camara* can be spectrally discriminated from all SPOT 6 bands but more significant from vegetation red edge 1(RE-1) to the short-wave infrared 1 (SWIR-1). The red edge reflectance region is sensitive to changes in plant eco-physiological status, including the vegetative analysis, which is directly related to plant health revealed through chlorophyll production. For Landsat 8, *Lantana camara* could be more spectrally distinguished from other land cover types at NIR, SWIR1 and SWIR2. Near-infrared (NIR) plays a critical role in boosting vegetation spectral" reflectance, SWIR1 discriminates moisture content of vegetation and soil SWIR2 improves moisture content of soil and vegetation which helps in the spectral discrimination of land cover types (Laurie and Marthick 2008). Studies have also shown that *Lantana camara* is not significantly distinguished" from other land cover types in the visible portion of the electromagnetic spectrum. Moreover, in healthy green vegetation, the pigment in leaves results in a significant minimum reflectance "in the visible part of the electromagnetic spectrum;" however, such a distinction is limited between *Lantana camara* and other land-cover types in this region. In NIR, reflectance dramatically increases where structural variability between *Lantana camara* and other land cover types plays a significant role in the discrimination process (Tsai et al. 2007).

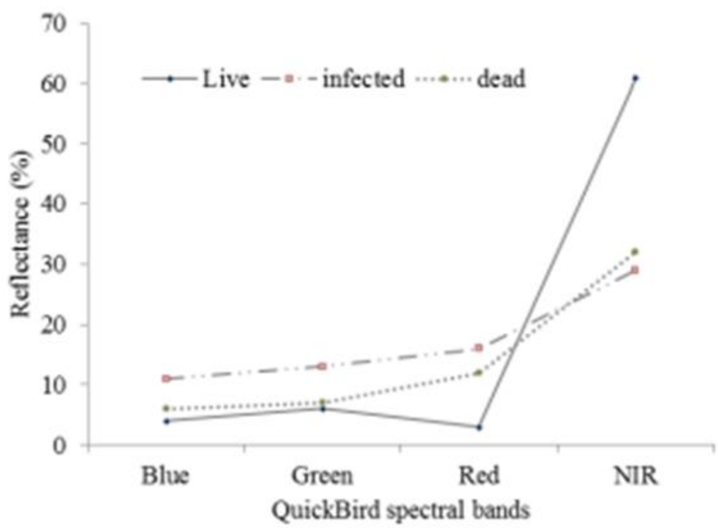

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Figure 2.3 Average field-derived reflectance of live, dead, and infected *Lantana camara* spectrally resampled to four QuickBird bands (Curatola Fernández et al. 2013).

2.5 Predictive techniques that have been used in mapping *Lantana camara* distribution

Various models have been used in mapping the distribution of *Lantana camara*. "For example, Priyanka et al. (2013) conducted a study to build spatial invasion distribution models for *Lantana* using 3 (three) species distribution modeling algorithms, namely, Maxent, Biomapper, and Garp. In the study, 33 ecological variables were utilized to predict the distribution of *Lantana camara*, out of these, 108 were considered as potential predictors. The results of the study showed that

Maxent model outperformed the two other models with accuracies ranging from 78% to 80 % for a very low to a very high *Lantana camara* distribution, respectively. Masocha et al. (2004) mapped *Lantana camara* distribution using Support Vector Machines (SVM) and Neural Networks (NN) classifiers. These classifiers were combined with Geographic Information System (GIS) expert system involving terrain and habitat position data. The combination of expert system and neutral networks had a satisfactory accuracy of 83%. Furthermore, Fernando et al. (2008) conducted a study to identify the spatial distribution of *Lantana camara*. "The study used Normalized Difference Vegetation Index (NDVI) along with a supervised" maximum classification, yielding an accuracy of 92%. Samarajeewa (2013) used Convolutional Neural Networks (CNN) on aerial images in the identification *of Lantana Camara* distribution. According to the study, CNN classified 967 flower species at an accuracy of 55.2%. CNN successfully recognized *Lantana camara* flowers yielding an accuracy of 94.6%. The proposed model successfully identified the occurrence of *Lantana camara* on aerial images. This section has shown that most predictive techniques used both environmental and remotely-sensed data for predicting the distribution of *Lantana camara.* A deeper exploration of the role of remote sensing is imperative.

2.6 Remote Sensing of *Lantana camara*

Traditional techniques to map *Lantana camara* include visual interpretation, and field surveys. According to Dube et al. (2016), traditional methods have a negative impact on the environment and they are unfeasible for large-scale implementations. Dube et al. (2016) further revealed that, these methods are very demanding in terms of field work and they require large volumes of additional data for analysis which is exhausting, costly and time-consuming. Most traditional techniques have been ineffective in identifying and mapping the spatial distribution of *Lantana camara*, particularly on a regional scale. Bunce et al (1992), utilized sample based field surveys of 508 1-km^2 on Britain's land-cover map to represent the distribution of *Lantana camara*. The spread of *Lantana camara* into new regions was poorly presented because the study depended on assumptions and restricted field data. These methods are not very accurate, since they do not incorporate the time series, and they are logistically and technologically unsustainable (Henry et al. 2011). According to Oumar (2016), the main challenge with hand drawn maps was that they yielded poor accuracies due to the tools and material features that were used to draw the maps including human errors as well as the size of the instruments.

Several satellite sensors have been utilized in the past decades to gather data on *Lantana camara* 2016). Remote sensing applications provides a good alternative for mapping invasive *Lantana camara* species, hence has gained substantial momentum in the last decades globally. Literature searches on published remote sensing journals indicated an increase in the work done on mapping the spatial distribution and configuration of *Lantana camara* (figure 2.4). Figure 2.4 further illustrates an exponential increase in the number of publications over the years.

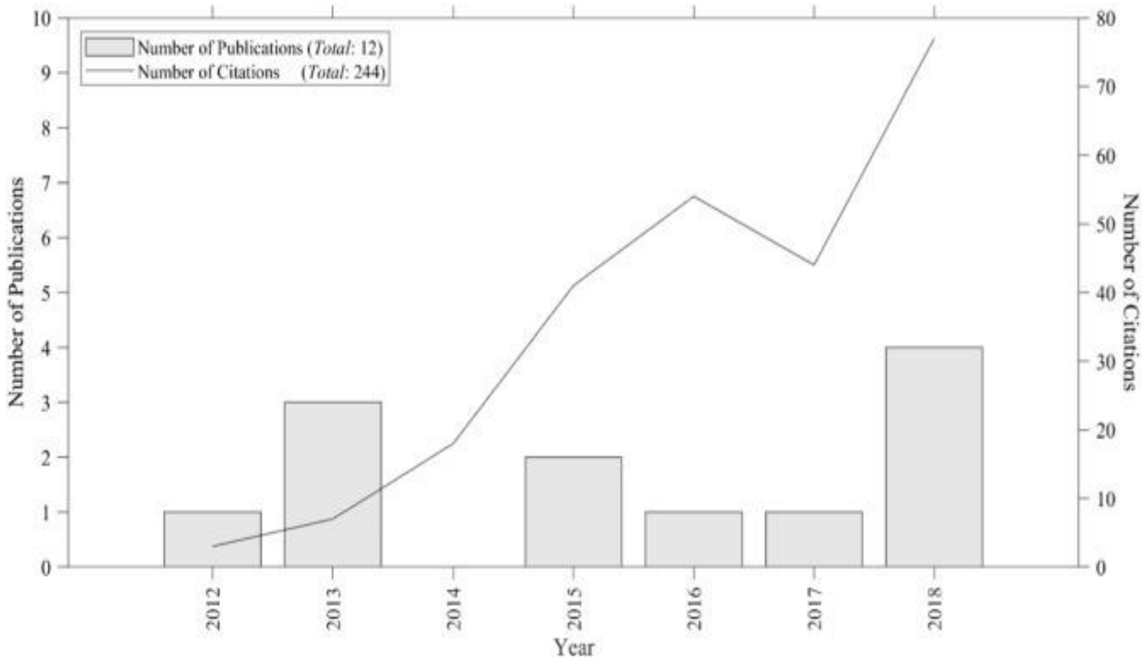

Figure 2.4: Number of remote sensing publications on *Lantana camara* over the years (Wand et al. 2019).

In mapping the distribution of *Lantana camara* remote sensing technology has been confirmed to be crucial because of the quality of its high temporal and spatial data (DeFries et al. 2004), and it is also useful at different spatial scales, it is healthier, quicker and more efficient manner (Carreiras et al. 2012). In the field of biological invasions, there is currently a significant interest in remote sensing technology, with its multi-spectral and high-resolution data. (Joshi et al. 2006). Geographic Information System (GIS) and Remote sensing technologies can provide data inputs for predicting areas vulnerable to invasion of *Lantana camara*. Moreover, “these technologies offer potentially valuable tools for” detecting, “mapping and monitoring” *Lantana camara* (Johnson 1999). Remote sensing applications provides a good alternative for mapping invasive *Lantana camara* species, hence has gained substantial momentum in the last decades globally (*figure 2.4*).

“Various remote sensing data types have been used for the detection of invasive species” to date (Huang and Asner, 2009), from multi-spectral and hyperspectral satellites, to airborne or Unmanned Aerial Vehicle (UAV) data, and aerial photos. Significantly, hyperspectral imagery is usually applied for invasive plant species (Bradley 2013), as the large number of spectral bands allows the differentiation of even subtle differences in plant chemistry, in order to detect the target species. Lawrence et al. (2016) conducted a study and used multi-spectral data to differentiate vegetation into taxonomic levels. SPOT 6 and vegetation indices such as Normalized Differences Vegetation Indices and simple ratio were applied in the detection and mapping of *Lantana camara* in the Kwa-Zulu Natal rangelands. Results produced an Overall Accuracy of 75% (Oumer 2016). Numerous studies used multispectral data to detect and map invasive *Lantana camara* plants (Huang and Asner 2009), mainly due to an improvement in the spatial resolution of multispectral imagery. Coarse spatial resolution images have largely yielded poor classification results. For example, Carson et al (1995) unsuccessfully mapped *Hieracium pratense* at species level using Landsat TM that has a spatial resolution of 30 m. In addition, variations in brightness caused by terrain can also cause poor classification results (Cuneo et al. 2009).

A common problem in *Lantana camara* detection is that taller species may obstruct invasive alien shrubs and thus induce biased classification results. This is opposed to dense monotypic species stands which are easier to detect and result in a greater accuracy (Joshi et al. 2004). Multiple research studies, including those of Odindi et al. (2014) and Schmidt et al. (2010), have shown the effectiveness of SPOT data in mapping invasive plants. A study by Lawrence et al (2006) have shown the usefulness of Worldview-2 in and SPOT 5 imagery in mapping *Lantana camara* in South Africa which produced satisfactory accuracies of 78.22% and 84.74% using random forest algorithm due to improved spatial resolution. The launch of new innovative satellite imagery, with a higher spatial resolution and a wider swath width, offers unrestricted prospects for detecting and mapping *Lantana camara*. Rima et al. (2016) used Sentinel 2 and Pleiades in detecting alien invasive Prosopis and Vachellia species in Kenya. Results revealed that invasive species in the study area colonized urban centers and near water bodies. The study also showed that the areas dominated by agricultural activities are largely occupied by alien plants. Apart from mapping invasive species and potential areas for invasion, remote sensing has also been applied in quantifying vegetation recovery in cleared areas.

2.7 Remote sensing of restored areas

Ecological restoration is the practice of re-establishing and renewing destroyed environments after the damage caused mainly by anthropogenic activities (Apfelbaum and Chapman 2014). It is mostly driven by the observation that there has been a great increase in the number of ecosystems that have been destroyed and that there are limited undamaged environments to protect. Ecological restoration aims at reinstating, maintaining and managing areas that have been destroyed by the Invasive alien species (IAS). The Intention of ecological restoration is to supply a range of ecological services, for example, the identification of invasive species and site assessments, the preparation of a control and removal plan, the mechanical and hand extraction of targeted invasive species, the application of herbicides, as well as and maintenance and site monitoring. Therefore, remote sensing is one of the few methods used in monitoring restoration in previously affected regions (Samarajeewa 2013).

Meronoi et al. (2017) used remote sensing to conduct a study in Senegal that was based on monitoring the land restoration interventions in semi-arid environments, with a before–after control-impact statistical design, using remote sensing technology. Hence, before-after control method of intervention for NDVI (Normalized Difference Vegetation Index) was used as a proxy for vegetation cover and restoration interventions to assess biophysical impacts. Results demonstrate that a critical improvement in vegetation cover was detectable in just 33% of the examined interventions, which is constant with independent qualitative evaluations based on field observations and visual analysis of high-resolution imagery. This method is to be used by rural development agencies for the first screening of restoration interventions. Liu et al. (2019) assessed forest restoration with multi-temporal FormoSat-2 remote sensing imagery and used the Three-Level Decision Tree (TLDT) approach to map bare and low-vegetated lands, forests and shadowy areas consecutively, by integrating three spectral indices for a better restoration assessment. The results yielded an overall accuracy of 96.8%, despite the divergence close to the boundary of each class caused by various resolutions. This work supports the use of multi-temporal remote sensing imagery as a reliable source of data for assessing the effectiveness of forest restoration on a regular basis (Venkatappa et al. 2019). This work also serves as the basis for studying the global trend of forest restoration in the future. However, an investigation of literature has shown that, little has been done in terms of the remote sensing of rehabilitated areas of invasive species, especially *Lantana camara*.

2.8 Future research directions and conclusions

Evidence from literature reveal that, studies using remote sensing applications for detecting and mapping *Lantana camara* has substantially increased over the past decade. However, there is a scarcity of literature regarding the management of *Lantana camara*, and more aspects of the remote sensing of *Lantana camara* still need to be explored. Extensive work needs to be done on escalating the use of remote sensing in order to offer improved projections in mapping and monitoring the spatial configuration and ecological restoration of *Lantana camara,* where the weed has not yet been eradicated (Masocha et al. 2004). Satellite images such as Landsat, Sentinel and SPOT enable the detection of invasive species among other land cover classes (Oumar 2016). However, challenges observed in remote sensing *Lantana camara* involve corresponding of spectral signatures between *Lantana camara* and other vegetation types, resulting in low classification accuracy. For researchers and managers to be able to make good decisions, the use of high- resolution images is of paramount importance as they enable the enhanced tracking of the spatial distribution and the spread of invasive species with acceptable accuracies (Kganyago et al. 2018). These images do not only enhance monitoring but are also essential in both regional and global studies on deforestation, nature conservation, and biodiversity monitoring (Taylor et al. 2012). Multi-date satellite images need to be used as they permit monitoring of the dynamic features of a landscape. Thus, they can also be used to draw conclusions on whether the invasive species are increasing, decreasing or if they have reached an equilibrium (Joshi et al. 2004). Although there have been improvements in the adoption of efficient remote sensing applications in mapping and monitoring of *Lantana camara*, little has been done on ecological restoration; thus, there is need for future studies to focus on invaded and cleared areas, as well as those that has not been invaded.

CHAPTER 3: MAPPING THE SPATIAL DISTRIBUTION OF *LANTANA CAMARA* DATA IN THE MPUMALANGA COMMUNAL AREAS OF SOUTH AFRICA, USING HIGH- RESOLUTIO SPOT 6 DATA

Abstract

Agro-ecosystems play a critical role in rural economics and contribute towards the national economy. These areas are, however, currently under bush encroachment. Timely information on potential hotspot and affected areas is required for management purposes. We assess the spatial distribution patterns of *Lantana camara* invasion in savanna rangeland ecosystems, of one before and after clearing (2014, 2016 and 2018), using the high-resolution SPOT 6 data, in Agincourt, South Africa. Maximum likelihood classification algorithm was applied on SPOT 6 to detect and map areas affected by this invasive species. Further, different accuracy assessment measures (e.g. Producer Accuracy (PA), User Accuracy (UA) and Overall Accuracy (OA)) were used to assess the validity of the classification results namely built-up areas, bare areas, uninvaded areas and invaded areas. The results demonstrated that the occurrence of *Lantana camara* in rangeland ecosystems can be mapped with high accuracy. An overall accuracy of 81.29% was attained for 2014, 86.85% for 2016 and 88.69% for the year 2018. It was further observed that the occurrence of *Lantana camara* in 2016 was minimal, when compared to 2014, but the results indicate that there was regeneration in 2018 in previously cleared areas. In 2014 approximately 40.84% of the area was covered by *Lantana camara*, in 2016 it was 25.19% and in 2018 it was 27.02%. Overall, the findings of this study underscore the need for the continuous monitoring of affected areas, especially after clearing, and to continuously advise on areas that are at risk of the potential re-establishment of invasive weeds.

KEYWORDS: Agro-ecosystems, ecological restoration, encroachment, mapping, invasive weeds.

3.1 Introduction

The spread of alien invasive species is extensive globally, and it affects the biodiversity, by outcompeting the native plant species for resources and causing direct predation and ecosystem damage (Veitch and Clout 2002). Yusuf (2016) showed that roughly 10 million hectares of land has been invaded by invasive alien species (IAS) in South Africa. Several invasive species have been detected in parts of the country which includes Mpumalanga, Limpopo and KwaZulu-Natal (O'Connor 2005). For instance, Thamaga and Dube (2018) detected invasive *water hyacinth* in the greater Letaba River system in Limpopo, whereas, Ndlovu et al. (2018) modelled the potential distribution *Rubus cuneifolius* also known as American bramble in Ukhahlamba Drakensberg Park in KwaZulu-Natal. Furthermore, Matongera and Mutanga (2016) monitored the spatial distribution of *Bracken fern* in Cathedral Peak in KwaZulu-Natal. Peerbhay et al. (2005), detected *Solanum mauritianum* in the Sappi’s Hodgsons forest plantation in KwaZulu-Natal.

Environmental reports including field surveys, show that *Lantana camara* is one of the most noxious species, therefore, ranked as one of the top-ten watch-out species that needs to be eradicated with immediate effect (Quentin et al. 2014). It has poisonous seeds, which increases mortality rate when ingested by livestock and wildlife (Gooden et al. 2009). This weed threatens the ecosystem, on both a community and global scale, resulting in biodiversity loss and the shifting of richness of species richness in the forest fragments (Pimm 1986). Current discussions on alien invasive weeds have strengthened the ongoing arguments on strategies to control and manage *Lantana camara* (Bhagwat et al. 2012). The toxic species also can survive under any harsh and intolerant circumstances such as droughts, floods and high temperatures (Carey et al. 1996).

The spatial distribution of *Lantana camara* was traditionally obtained by means of field surveys and visual interpretations. Such techniques require additional data for analysis and they are time consuming, laborious and cost efficient (Dowling and Accad 2003). Moreover, these methods have been restricted to small areas and did not produce accurate results (Ward and Morgan 2014). Alternatively, remote sensing offers timely, precise and accurate information on mapping the spatial distribution of *Lantana camara*, and it offers many opportunities in a wide variety of applications, including the monitoring of wildlife characteristics and natural resources and inventory assessments of plant species, such as *Lantana camara*. Previous studies have used medium spatial resolution satellite imagery for mapping the spatial distribution of *Lantana camara*. For example, Dhau (2008) used Landsat TM and Aster to map and monitor *Lantana camara* invasion in three land tenure systems in Zimbabwe and produced accurate results.

Remote sensing technologies have developed a solid strategy for ecological invasive species mapping and can therefore be used to come up with good detecting and monitoring methods of alien invasive species (Kimothi et al. 2010). Which then offers better predictions in providing progressed required spatial data to comprehend the spread and spatial distribution of *Lantana camara* (Matongera et al. 2016). The consistent evaluation of invasive species, utilizing remote sensing data, has expanded in recent years, improving the understanding of the spectral reflectance properties of vegetation (Blackburn and Pitman 2010). Kekana (2008) revealed that, the use of spectral data from high spatial resolution sensor such as SPOT 6 with 1.5m resolution offers the potential for mapping and discriminating *Lantana camara* even in areas that are prone to its invasion. SPOT 6 datasets permit repeated regional scale mapping and monitoring with a daily revisit to any point on the globe (Priyanka 2013). The sensor can adjust the image acquisition angle, which qualifies it as one of the key data sources appropriate for large-scale applications, particularly in areas with limited resources (Sibanda et al. 2016). Current studies revealed that high spatial resolution sensors such as SPOT 6 could accurately classify *Lantana camara* because of their improved spectral and spatial resolutions (Oumar 2016; Kganyago et al. 2018, Yusuf 2016). Hence, this study sought to map the spatial distribution of *Lantana camara* invasion in savanna rangeland ecosystems overtime using high-resolution SPOT 6 data.

3.2 Materials and methods

3.2.1 Field data collection and pre-processing

Field data were collected from the 12th to 14th of April 2018, which are the dates that coincide with the image acquisition dates. *Lantana camara* and other land cover classes location was recorded using a hand-held Trimble Juno 3B Global Positioning System (GPS) receiver at Sub meter accuracy. Stratified random transects from the Agincourt shape file were generated using

ArcGIS 10.3 software. The transect co-ordinates were successively uploaded on the GPS that was used to navigate to the sampling sites in the study area. Systematic sampling was used, whereby a quadrant (50 cm^2) was measured within the 30-40 m transect, after every 10 m. The location recorded for other land cover classes include bare fields, built-up areas, invaded area and uninvaded areas. A total of 385 sample points were used in the study. Thus 70% were used for training, while 30% were used for validation. This proportion is used mostly when conducting a supervised classification procedure as it requires training datasets and then after the training samples are used to train the model to classify the image into a map. After the map has been classified field measured points are required to validate the accuracy of the classification map. Literature (Zhen et al. 2013, Reitermanova 2010 and Xu and Goodacre 2018), illustrates that the 70/30 splitting of data is the most optimal way in terms of classification. The GPS-measured locations were captured in a table format in Microsoft Excel and then converted into point map in ArcGIS 10.3 software.

3.2.2 Remote sensing data acquisition and processing

SPOT 6 is a high spatial resolution dataset that was acquired from South African National Space Agency (SANSA). This satellite (SPOT 6) is characterized by its high-resolution and the ability to provide 1.5m high-resolution products with five spectral bands, and a daily revisit anywhere on earth, with a total coverage of 6 million km^2 per day. Furthermore, SPOT 6 is made up of five bands including a 1.5m panchromatic band and four multispectral bands which are Red, Green, Blue, and Near Infrared consisting of 6m resolution each. The Pan sharpened 1.5m color image is available as Bands 3 and 4 merges. The five bands are namely, Panchromatic: 450-745 nm, Blue: 450-520 nm, Green: 530-590 nm, Red: 625-695 nm, Near Infrared: 760-890 nm. In this study all of the five bands were used. SPOT 6 images were then tested in mapping and monitoring the spread of *Lantana camara* in Agincourt, Mpumalanga. This study utilized a cloudless satellite dataset (SPOT 6) covering the study area. SPOT 6 provide continuity of high-resolution, with 8bits of Radiometric Resolution and a swath- width of 60km.

3.2.3 Image classification and accuracy assessment

Field data collected points were over-laid on the satellite images in Arc map 10.3 where the study area was also extracted. All bands that offer a significant discrimination of *Lantana camara* from other land cover types were used in mapping the spatial distribution of *Lantana camara* over-time using the supervised maximum algorithm. Stratified random sampling was used in splitting the collected data i.e. 70% was used for training of the classification whereas 30% was used for validation purposes. The chosen land cover classes were cross tabulated on confusion matrix against the land cover classes to determine classification accuracy. The agreement between the classification results and ground truth data was measured by using the producer accuracy (PA), user accuracy (UA) and overall accuracy (OA) generated from the confusion matrices.

3. 3 Results

3.3.1 Change detection assessment

Table 1 presents percentage change of *Lantana camara* and other land cover types in hectares. It can be observed that invaded areas decreased from 2373.8 ha in 2014 to 626.85 ha in 2016, resulting in a total decrease of 1746.95 ha. However, as invaded areas decreased during this period, the bare areas also reduced by a total of 756.01 ha, from 3566.01 ha in 2014 and 2810.00 ha in 2016. Moreover, uninvaded class increased with a total of 23.01 ha from 2014 to 2016. Furthermore, from the year 2016 invaded species re-established themselves from 626.85 ha to 773.57 ha in 2018, contributing to a total increase of 146.72 ha. Expressed in percentage changes, table 3.1 also indicates that uninvaded areas covered a total of 18.19% in 2014 and increased to 46.76% in 2016; a difference of 28.57%. The decrease in invaded area could be attributed to direct clearing measures embarked upon by the community members, as well as other workers of different program including disaster programs, hence, leading to cleared areas of 32.21% in 2016. Over the period of two years, trend of uninvaded areas has however increased to 40.89% in 2018, which led to a total increase of 5.9% and a total increase of 22.7% from 2014 to 2018, with a decrease of cleared areas to about 5.48%. Hence, the trend indicates that, *Lantana camara* weed is capable of re-establishing itself at a fast state if not well eliminated.

Table 3.1: Area change overtime in hectares.

AREA IN (ha) OF CHANGE OVER TIME			
CLASSES	2014	2016	2018
Bare areas	3566.1 (16.92%)	2810 (32.9%)	1145.6 (25.73%)
Built-up areas	395.78 (7.34%)	1553.7 (29.13%)	2127 (27.14%)

Uninvaded	1267(18.19%)	1290.1 (46.76%)	2456.5 (40.89%)
Invaded	2373.8 (40.84%)	626.85 (25.19%)	773.57(27.02%)
Cleared areas	0 (0%)	2282.5 (32.21%)	1123.1 (26.73%)

3.3.2 Image Classification Maps

Figure 3.1 displays the spatial distribution and rate of change of *Lantana camara* in savanna ecosystems over time and space. Results indicate that, land cover types (Bare areas, Built-up areas, Uninvaded areas, Invaded areas and Cleared areas) in the study area show marked changes during the period from 2014 to 2018. This is proved as there is a visible increase in uninvaded areas and reduction of invaded areas due to clearing, but then invaded areas increased again from 2016 to 2018 with a decrease in uninvaded areas. Furthermore, observations show that the invaded areas are spatially changing despite the area they are in, whether mountainous or gentle areas, they just thrive. Other land cover types, namely bare surfaces, built-up areas, as well as uninvaded areas (shrub-land, grassland), also increased and decreased over the three years to keep a balance in the ecosystem and to survive, they still failed, as they were overpowered by this toxic species.

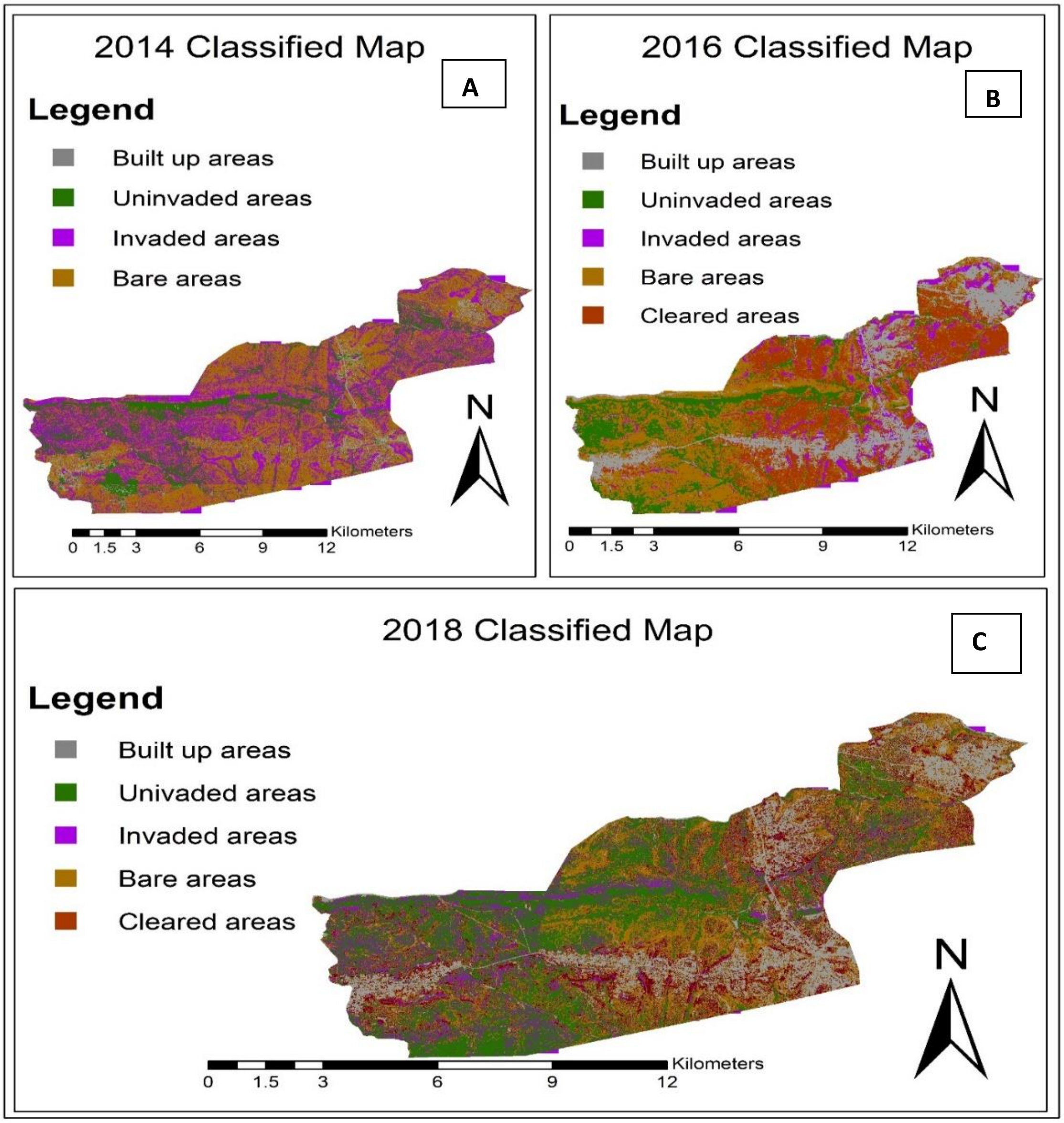

Figure 3.1: Classification map of *Lantana camara* species and other land cover type's overtime.

3.3.3 Accuracy assessment

Overall accuracy assessment of land cover was validated using confusion matrix which are shown in table 3.2. The results indicate that the use of SPOT 6 produced satisfactory overall accuracy greater than 80% for all the years, although 2014 had the lowest accuracy of 81.29% as compared to mapping *Lantana camara* over time in the years 2016 and 2018. Most of the classes produced a good user accuracy (above 80%); for instance, *Lantana camara* had a user accuracy of greater than 75% for all the years.

Table 3.2: Accuracy assessment

ACCURACY ASSSESMENT						
	2014		2016		2018	
	PA	UA	PA	UA	PA	UA
BUILT UP AREAS	100	81	100	76	100	75
BARE AREAS	79	82	83	87	74	77
UNINVADED	66	76	74	80	6 4	78
INVADED	83	77	95	88	86	78
OVERALL ACCURACY	**81.29%**		**86.85%**		**88.69%**	

3.4 Discussion

This study sought to map the spatial distribution of *Lantana camara* invasion in Agincourt, Mpumalanga, South Africa. The results of this study demonstrated that the freely available SPOT 6 multispectral sensor with high-resolution, can detect and map *Lantana camara* with high overall accuracy results. A satisfactory overall accuracy of 81.29% was attained for 2014 classification results which is satisfactory, however, it appears to be the lowest as compared to the years 2016 and 2018 as they both with yielded accuracies greater than 85%. According to Rocchini et al (2015), multispectral imagery produces high classification accuracy assessments. The availability of SPOT 6 multispectral sensors offers exceptional possibility in detecting of the spatial distribution of *Lantana camara* species. The radiometric characteristics of this sensor can produce appreciable differences in the retrieved radiometric quantities. Therefore, the results demonstrate that the high spatial resolution SPOT 6 sensor can detect and map *Lantana camara* with satisfactory overall accuracy results. The classification of *Lantana camara* was successful due to its leaves exhibiting dense hairs and surface textures where *Lantana camara* is situated, hence, affecting the reflection of radiation resulting in unique spectral signature as compared to other vegetation or land cover classes present in the area (Adam 2016; Skidmore 2002). These classification results are supported by the study done on the detection of Giant Reed (*Aurundo donax*) which showed that imagery with higher spatial resolution increased detection accuracy (Everitt et al. 2008). SPOT 6 produced great accuracy results due to its characteristics such as the 1,5m resolution in visual and NIR bands, which benefits its applicability to large areas as well as its daily revisit time and the wider viewing angle. The strength of the high spatial resolution SPOT 6 multispectral sensor explains its optimal and an alternative for *Lantana camara* mapping (Shoko and Mutanga 2017).

According to the results found the approximate total area coverage data for both 2014 and 2018 is 7625, 78 ha, which is less than the area coverage for the year 2016 which is 8540, 05 ha for the table 3.2. The output classification of the three images are compared in table 3.2, which display invaded areas, uninvaded areas and other land use classes change from 2014 to 2018. Furthermore, results indicate that, invaded areas had a total decrease of 1746, 95 ha from the year 2014 to 2016. The increase in trans-boundary movement and global economic trade accelerated the spread of *Lantana camara,* thus, made it difficult to ignore and control the spread of alien plants across the country (Kalita et al 2012). Furthermore, *Lantana camara* is mostly introduced in areas for agriculture or ornamental purposes (Lake George Association, 2019), hence, resulting in high distribution of the species in 2014. Thus, some of the land-cover classes e.g. built-up areas were rarely detected due to the invasion. However, as a means of control, Expanded Public Works Program (EPWP) workers, Disaster Programs Workers, and community members worked together in clearing invaded areas. A few control methods were used to eradicate plants, as approved by the State of the World Plants (2017), including chemical, mycoherbicide and mechanical methods. Chemical and mycoherbicides methods use herbicides to eliminate plants, while mechanical methods include the physical action of removing plants, either by uprooting, or the felling of weeds. Similar control measures have also been used in previous studies. For instance, Ritchardson and Wilgen (2004) used similar methods for the management of invasive species in South Africa, and they obtained satisfactory results. As invaded areas decreased during the clearing period, bare areas also reduced by the total of 756.01 ha from 2014 to 2016. However, the uninvaded class increased by a total of 23.01 ha. From the year 2016 to 2018 the invaded species re-established themselves from 626.85 ha in 2016 to 773.57 ha in 2018, contributing a total increase of 146.72 ha. The possible reasons for the re-establishment of *Lantana camara* may be due to the failure to do follow-up control, after the initial attempts of eradication, and failure to remove the resulting rootstock. This is consistent with the study conducted by Montague et al. (2007) in mapping Purple Loosestrife (Lythrum salicaria, Lythraceae) and found similar results of species re-establishment.

Supervised maximum likelihood classification was also used in the study to compare distribution patterns of *Lantana camara* for all the three years respectively. The information from classification was used to determine the pattern and spread of *Lantana camara* overtime, further the information from the classification map is valuable for achieving effective control and eradication of the species. It is important to consider the distribution of *Lantana camara* for the management and control of the invasive weed. Understanding of the spatial distribution of the weed will further assist environmental managers to monitor the possible changes in the environment and establish a relationship between the invader and changes in the ecosystem particularly in the affected habitat. The results further demonstrated that the weed occurred in clusters or patches in 2014, which indicated that there was a greater establishment and dominance of the species than in 2016 and 2018. Moreover, the *Lantana camara* invasion lead to decrease in agricultural productivity and land for grazing. Large patches can be targeted for removal and for preventing them from spreading further. On the other hand, small patches have demonstrated new introductions, which need to be targeted for control and removal purposes.

4. Conclusions

Findings of this study reveal that, SPOT 6 multispectral sensor with its high-resolution can provide a cost- effective opportunity for regional scale detection, mapping and monitoring of *Lantana camara* weeds. In this study, supervised (maximum likelihood) classifier was used to track the spatial distribution of *Lantana camara*. Results show that *Lantana camara* invaded a large area in 2014, began to decline till 2016, and eventually inclined a bit in 2018, as it re-established itself. Furthermore, results show that as the alien weed was eradicated, the indigenous species started increasing and covered areas which were previously invaded by *Lantana camara*. Therefore, the accuracy of these results show the potential of using SPOT 6 for mapping the invasive *Lantana camara* species and for prioritizing it for eradication, in order to prevent it spreading further on a regional and local scale. Overall, the study showed that the spatial configuration of SPOT 6 was significant in that it provided useful and necessary information for effective land management, invasive weed management, and the prioritization of conservation plans.

CHAPTER 4: OBJECTIVES REVIEWED AND CONCLUSION

4.1 Introduction

Lantana camara is an invasive plant species that is distributed widely in subtropical and tropical regions (Day 2009). The spread of this noxious weed into environments can cause major distraction to native or indigenous plants, due to its high consumption of water. The spatial extent of an invasive plant species needs to be understood, before proper management strategies can be implemented. Accurate techniques that can specifically portray species information are required for mapping the spatial distribution and configuration of *Lantana camara.* Even though much work has been done on mapping *Lantana camara,* most of these studies have focused on regional scale mapping, but little has been done on a local scale. However, it is essential to note that most of the areas affected by *Lantana camara* at a local scale are mainly used for subsistence agricultural activities.

4.2 Objective 1: To review the progress and challenges in mapping *Lantana Camara* weeds using multi-spectral remotely sensed data.

The study reviewed the progress made in mapping the spatial distribution of *Lantana camara* species. Results from previous studies revealed that spatial and spectral resolution were paramount limitations in mapping the spatial distribution of *Lantana camara*. Remote sensing has proven advantageous in providing fine spectral and high spatial resolution capabilities that are essential to offer precise and reliable data on the spatial distribution of *Lantana camara*. Previous studies mostly utilized medium spatial resolution sensors such as Landsat 7 and SPOT 5 which has been constrained due to inadequate spatial and spectral resolution which were paramount limitations in mapping the spatial distribution of *Lantana camara*. High-resolution sensors, for instance, QuickBird, SPOT 6 and WorldView-2 have a spatial resolution of less than 5 m and can accurately detect invasive *Lantana camara* weed on a regional scale. It is therefore recommendable to utilize high-resolution sensors with regards to magnitude of mapping accuracy expected in that specific study and the size of *Lantana camara* patches.

4.3 Objective 2: To map the spatial distribution and rate of change of *Lantana camara* in savanna ecosystems over time and space

SPOT 6 data established prodigious performances in *Lantana camara* mapping. Based on the findings from this study, multi-data SPOT 6 data was utilized to map the spatial distribution of *Lantana camara* and assess its change overtime in Agincourt, Mpumalanga. The results showed changes in area covered by *Lantana camara* from 2014 to 2018. In 2014 *Lantana camara* invasion covered about 40.84% (2373.8 ha) of area classified as invaded area, 25.19% (626.85 ha) in 2016 lastly, 27.02% (773.57 ha) in 2018. These results shows that in 2018, *Lantana camara* re- established itself. This could be due to the failure to monitor the cleared areas after its eradication. For example, literature showed that failure to apply herbicides as a control method, and failure to remove root-stocks when eradicating the plant leads to re-establishment of the weed (Crooks and Rilov 2009).

4.4 Conclusion

The overall aim of the study was to map the spatial distribution of *Lantana camara* invasion in savanna rangeland ecosystems overtime using high-resolution SPOT 6 data, in Agincourt, South Africa. The results of this study emphasized the ability of multispectral remote sensing satellite imagery, in terms of accurately detecting, mapping and assessing the changes in *Lantana camara.* SPOT 6 with its improved spectral and spatial resolution makes the sensor one of the key primary data sources that are suitable and practical for regional applications especially in limited resource areas. Newly launched high-resolution SPOT 6 multispectral sensor can provide strong capabilities in detecting and mapping the invasive *Lantana camara* weeds at both local and regional scale. Results from the study showed that, the spread and distribution of the weed was high in 2014 and the was a sharp decrease in 2016 due to clearing of the invaded area, with a slight increase in 2018, due to the failure of the follow up and control, after the initial attempts in the eradication process.

4.5 Recommendations

There is a rapid increase in alien invasive plants in South Africa and all the invasive plants present in the landscape need to be taken into consideration by land managers when coming up with mitigation methods. Therefore, future research studies in mapping invasive plants should conduct a time series analysis, so they can evaluate trend of the alien species.

Other research recommendations include:

- Conducting research studies which identifies areas that are at risk of IAP invasion, by allowing general discrimination between invaded areas and uninvaded areas.
- Further, research studies should be conducted on the negative effects of IAP clearing on biodiversity.

- Determining drivers of infestation, and the information will be useful in understanding environmental factors which favors the spread of *Lantana camara* and affects agricultural areas.

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