Developing fixed-point photography methodologies for assessing post-fire mountain fynbos vegetation succession as a tool for biodiversity management

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ABSTRACT

Areas of high biodiversity and complex species assemblages are often difficult to manage and to set up meaningful monitoring and evaluations programmes. Mountain Fynbos is such an ecosystem and in the Cape of Good Hope (part of the Table Mountain National Park) plant biodiversity over the last five decades has been in decline. The reasons are difficult to speculate since large herbivores, altered fire regimes and even climate change could be contributors to this decline which has been quantified using fixed quadrats and standard cover-abundance estimates based on a Braun-Blanquet methodology. To provide more detailed data that has more resolution in terms of identifying ecological processes, Fixed-Point Repeat Photography has been presented as a management "solution". However, photography remains a difficult method to standardize subjects and has certain operational limitations. These include: weather conditions (poor visibility results in poor images), camera resolution (a low resolution will underestimate the number of a small plants or amount of flowers and fruits/seeds), shadows and image bright spots result in an effective loss of data. Also, photography will always have "depth of field" problems and perspective distortions. This study aimed to develop an effective method of high-definition fixed-point repeated parallel panoramic photography that overcame these limitations to assess post-fire Mountain Fynbos succession.

By using the highest resolution Digital Single Lens Reflex Camera (Canon EOS 5DS R) and a 45 mm Tilt and Shift lens. Three images each 51 Megapixel in size were taken to expand the cameras field of view horizontally and vertically since the camera was orientated to produce portrait images. The images were then processed and enhanced using two modern computer programmes (Photoshop and Lightroom) that stitched these images into one and applied radiometrically (colour balance) and geometric corrections (so that images taken at different times can be overlaid).

By repeating this imagery at fixed points using marked out quadrats (3 m x 2 m) over different seasons, a large amount of data relating to species richness, structural assemblages and phenological characteristic can be obtained. Such data could include monitoring individual plants such as their growth rates, leaf development, flowering and seed production through to their senescence and death. Use of these enhanced photographic methods for Monitoring and Evaluation should improve the ability to better manage complex and species richness ecosystems.

A video has been prepared to demonstrate the methods developed in this study: https://www.youtube.com/watch?v=sdK3U-49Ezg&t=2s

KEYWORDS: Biodiversity management, Change detection, Fixed-point repeat photography, High-resolution images, Mountain Fynbos, Post-fire succession, Panoramic stitching, Spatial scales.

August of 2020

LIST OF ACRONYMS

FPRP	Fixed-Point Repeat Photography.
RP	Repeat Photography.
UAV	Unmanned Aerial Vehicles.
SANParks	South African National Parks.
HDR	High Dynamic Range.
TIFF	Tagged Image File Format.
MTEs	Mediterranean-Type Ecosystems.
CFR	Cape Floristic Region.
SNR	Silvermine Nature Reserve.
PP	Parallel Photography.
RGB	Red, Green and Blue.
HSL	Hue, Saturation and Luminosity.
B-B	Braun-Blanquet.
DOF	Depth of Field.

DECLARATION

I am Osama Alkalei, I declare that "*Developing fixed-point photography, methodologies for assessing post-fire mountain fynbos vegetation succession as a tool for biodiversity management*" it is my work. That this thesis has not been submitted or published before for a degree or any other qualification at this University or any other institution.

The thesis is based on work done by myself jointly with others, I have made clear exactly what I have contributed to myself and what it was done by others.

Signed ………………………………. **August 2020**

Osama Alkalei

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION AND BACKGROUND

Vegetation surveys and classifications are important in vegetation science, biodiversity conservation and environmental monitoring (Schwabe *et al.* 2011). These surveys and classifications also greatly assist in understanding differences and defining vegetation and habitat types (Černá and Chytrý 2005; Chytrý *et al.* 2011). The use of traditional digital image photographic methods in vegetation succession, monitoring and biodiversity management is well documented (Lucey and Barraclough 2001; Phattaralerphong *et al.* 2006; Laliberte *et al.* 2007). While Fixed-Point Repeat Photography (FPRP) is a specialization of traditional photographic methods used in vegetation studies, it has had various applications for the assessment of habitats and structural vegetation classifications (Table 1).

Table 1. Review of the traditional photographic methods of using fixed-point repeat photography (FPRP) in an assessment of components of vegetation habitat:

The traditional use of fixed-point repeat photography (FPRP)	**Reference**
Evaluate the number of flowers by separating colours from the background.	Adamsen et al. 2000
Daily analysis of mosses during drying and moistening cycles to develop a comprehensive understanding of their changing status under different climatic conditions.	Purcell 2000
Tracking the spring green-up in a deciduous broadleaf forest by using digital webcam images.	Richardson *et al.* 2007
Estimating fractional cover of green and senescent vegetation to develop an imagery inventory.	Laliberte *et al.* 2007
Short-term monitoring of the lichen cover biomass and arid-land.	Bowker *et al.* 2008
An analysis to investigate the extent of change and the response of vegetation cover from (1876-1971) within different landforms and land-use practices using 233 matched historical images from different years.	Hoffman *et al.* 2010
Assessment of understorey forest foliage cover.	Macfarlane *et al.* 2010
Extracting green fractional vegetation cover from digital images	Liu *et al.* 2012

Photography remains a difficult method to standardize subjects and has some operational limitations. Standardizing is difficult due to the seasons of the year, the amount of cloud cover and time of day, sun reflection as well as shadows and taking photos under windy conditions (Laliberte *et al.* 2007). Consequently, errors such as an underestimation of shorter plant heights may be introduced (Elzinga *et al.* 1998). The occurrence of bright spots in the photographic exposure renders details difficult to analyze (Cox and Booth 2009). A typical example includes the quantification of small flowers (Crimmins and Crimmins 2008). Similarly, shadows introduce dark spots that are difficult to analyze (Cox and Booth 2009). Other difficulties include camera resolution resulting in an under-estimation of small plants and their significance (Elzinga *et al.* 1998).

For many cameras, there is a difficulty of taking multiple photographs at the different focus of depth of field (DOF) to determine patterns between objects within the image. Photography will always have a DOF problem with some parts of the image being out-of-focus while other areas are in focus. Further, all photography will introduce perspective distortion which measures objects complicated (Chen et al. 2010). In photographs where there is a lot of change of exposure, such as shadows and or bright spots (under-exposed and over-exposed respectively) requires the taking of multiple over- and under-exposed images which are called exposure bracketing. These multiple images are combined to produce High Dynamic Range (HDR) images. High Dynamic Range (HDR) images render more detail in shadows and bright spots (Cox and Booth 2009) and effectively provide a better platform for analysis.

The objective of this study is to develop technological improvements to traditional photographic methods that partly overcome the issues described above. This is necessary to reduce the limitations encountered in the traditional photographic methods, and how these shortcomings can be addressed using the most modern digital platforms and post-processing of the images.

1. Rationale and Significance

1.1 The Importance and Benefits of Using Digital Imagery for Monitoring Long Term Vegetation Changes

Repeat photography (RP) is an interdisciplinary technique, which is being used to record many aspects of change over time as well as over widely differing landscapes to interpret a range of environmental parameters (Hall 2001; Webb *et al.* 2010). Monitoring is an important tool for understanding the structure and function of characteristics of ecosystems and local habitat and can be assessed using FPRP in the long-term (Noss 1990). In combination with other methods of study, it holds the promise of substantially more information and adds a perspective essential for use of the results in management (Hoffman *et al.* 2010; Emms 2013; Powell 2013; Latifovic and Pouliot 2014). Table 2 summarises the specific goals of image photography monitoring programs and their technological applications.

Table 2. Review of the advantages of using digital photography in monitoring vegetation changes:

Advantages of digital photography	**Type of image collection**	**Reference**
Provides a powerful method for environmental monitoring and investigating historical ecology over time.	FPRP	Hoffman *et al.* 2010
Investigates changes in archaeological features, assessing perceptions of change of land-use, fire effects.	FPRP	Webb *et al.* 2010
Assessment of vegetation cover, monitoring of agriculture and observing phenological events.	FPRP	Hoffman *et al.* 2010; Powell 2013
Referred to photography that is "near" remote sensing because of its ability to monitor vegetation phenology, and allows high temporal and spatial resolution datasets to be developed.	FPRP	Graham *et al.* 2006; Graham *et al.* 2010
Photography can reduce fieldwork time and data collection costs, which can enable data collection at a larger number of sites and using more quadrats.	Unmanned Aerial Vehicles (UAV) drone	Gobbett and Zerger 2014
While FPRP can be used at a small landscape scale (quadrat or plots) together with UAVs, image capture can complete the data collection and fill in gaps to provide a better interpretation of the landscape is derived.	FPRP-UAV	Gobbett and Zerger 2014
Automated photography such as time-lapse can also enable the capture of data at a higher temporal frequency (e.g. Hourly, daily, weekly) and may complement satellite-derived estimates of habitat ecosystem change.	FPRP-UAV	Gobbett and Zerger 2014
Vegetation response to climate change is often reflected in shifts in phenological events and an overall reduction in the health of vegetation and these easy recorded using photography.	UAV-Thermal camera	Maes *et al.* 2018

1.2 Long-Term Monitoring Using Photographic Records on the Fynbos Vegetation

The Repeat photography (RP) method has been used globally since the late 1800s for the assessment of arid, semi-arid and wetland environments (Cooke *et al.* 1985; Bahre 1991; McGinnies *et al.* 1991; Kull 2005; Davis 2013; Emms 2013). It has also been applied in studies of the historical changes in the vegetation, landscapes and cultural influences (Bass 2004; Nyssen *et al.* 2010; Rohde and Hoffman 2012; Davis 2013; Kamp *et al.* 2013; Emms 2013). It is used as a technique for environmental monitoring, investigating climate change and historical ecology (Byers 2000; Hoffman *et al.* 2010). Furthermore, it has been used as the main tool to assess the influence of fires, affect the weather condition on vegetation cover, as well as the impact of the livestock, land-use and changing the patterns in land cover over time (Byers 2000; Masiokas *et al.* 2008; Rohde and Hoffman 2012; Kamp *et al.* 2013; Powell 2013; Emms 2013).

In Africa, RP has been used since the 1950s (van den Berghe 1962), and studies have often focused on historical documentation of environmental changes (Davis 2013). In South Africa, RP has been used in the assessment of arid and semi-arid environments (Hoffman and Cowling 1990; Ward 1994; Hoffman *et al.* 2010; Rohde and Hoffman 2012; Davis 2013; Powell 2013; Emms 2013); while the use of historical photographs of the landscapes from the late 1800s through to the early 1990s provides useful information on long term environmental change (Kull 2005).

Many previous studies have focused on change in biodiversity over time and vegetation cover description of the Cape of Good Hope Nature Reserve (CGHNR), a section of the Table Mountain National Park (TMNP) (Table 3). Taylor undertook a floristic survey in 1969 of the south of the Cape Peninsula of South Africa, which now forms part of the TMNP (Figure 1; Table 3). He used 100 fixed point grids and standard phytosociological techniques based on species cover-abundance through different seasons (Taylor 1969). At the same time photographs were taken from most of the plots to further help in the species identification and for classification of the vegetation (Hoffman *et al.* 2010; Powell 2013). This analysis identified 23 distinct species assemblages existing in the Cape of Good Hope Mountain Fynbos vegetation (Taylor 1969).

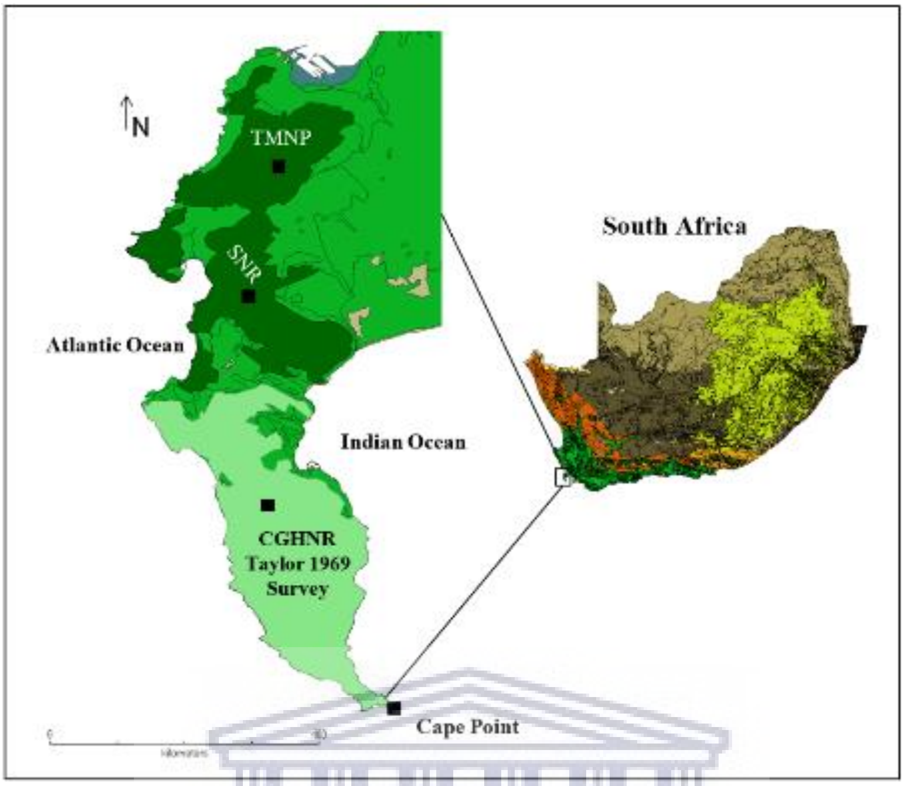

Figure 1. Map showing the location of the study area of Taylor's survey in 1969 within Good Hope Nature Reserve (CGHNR), that now forms a section of the Table Mountain National Park (TMNP), as well as the study site for this project, Silvermine Nature Reserve (SNR).

For the first time, FPRP was used by Powell (2013) as the main tool to investigate the rate and extent of vegetation change in the CGHNR over time, and to relate these changes to the key drivers of land use, climate, and fire (Rohde and Hoffman 2012; Powell 2013). This study permitted a better interpretation of the historical changes of vegetation cover over time-based on fire regimes and climate changes (Table 3), as well as to compare the changes against previous photographs (Powell 2013). These comparative studies showed that there was a small loss in species richness from 1966 - 2012, but there was a high turnover in plant species diversity (Thuiller *et al.* 2007; Powell 2013).

Table 3. Summary of studies at the Cape of Good Hope Nature Reserve (CGHNR), which determined the rate of vegetation change using repeat photography and historical data of the climate, fire regime, livestock and land-use (Powell 2013):

References/ Time	Approach	Methodologies	Result/ The extent of change over time
Taylor 1969	Used 100 grids, 10 x 5 m survey plots. Photographs to help in the identification classification of the vegetation.	Fixed quadrats. Standard cover-abundance estimates (Braun-Blanquet methodology).	Identified 23 distinct species assemblages. Classified the vegetation types and in 1966 he created a vegetation map from the plant species list.
Privett 1966 -1998	Re-examined 81 of Taylor's 1966 original plots.	Fixed quadrats. Standard cover-abundance estimates (Braun-Blanquet methodology).	A small loss in species richness. High turnover in species with a loss of 80.3% of the species and 79.3% new contribution of species.
Hall 1966 -2010	Relocated 26 of Taylor's 1966 original plots.	Fixed quadrats. Standard cover-abundance estimates (Braun-Blanquet methodology).	Species richness had declined by 25 %. A similarly in high species turnover to the previous research.
Powell 1966 -2012	78 historical photographs of Taylor's 1966 original plots.	Historical data on fires and climate. Aerial repeat photography. Ground repeat photography (FPRP).	Changes in the dominance of key growth forms (High species turnover). Change in the percentage of vegetation cover between sites.

A key benefit of FPRP is the ability to resolve more detail than conventional field sampling can provide. It may permit more frequent sampling since the time in the field is shorter so change detection can be more precisely undertaken. It allows data capture from the images to be re-analysed and even alternative hypotheses to be tested. Consequently, FPRP provides a useful methodology for long-term landscape and biodiversity management (Hoffman *et al.* 2010; Davis 2013; Emms 2013). The use of FPRP is increasingly being employed within organisations mandated to manage biodiversity such as South African National Parks (SANParks) (Table 4) with has incorporated the technology for biodiversity monitoring in National Parks of South Africa (Mcgeoch *et al.* 2011).

Table 4. Summary of South African National Parks (SANParks) use of digital photography monitoring:

The use of the FPRP in SANParks	Reference
Maintenance of biodiversity	Reyers and McGeoch 2007
Management of burn regimes and assessing the changes that might occur under changes in climate regimes.	Masubelele *et al.* 2013
Assess the impacts of the herbivores and climate on vegetation floristic and structure.	Masubelele *et al.* 2013

1.3 The limitations of using Repeat Photography (RP)

Despite the ability for increased resolving resolution power through the use of RP, limitations for long-term monitoring have been reported and these are summarised in Table 5.

Table 5. The limitations of using Repeat Photography (RP) and possible solutions:

Issues	Problems	References	Solutions
Determination of leaf area	Difficulty in the separation of a woody plant stem from leaves.	Phattaralerphong *et al.* 2006	Using a high-resolution camera and shooting in RAW format reduce these issues.
Panoramic imagery	Image alignment that reduces the overlapping quality of the resulting panorama.	Lucey and Barraclough 2001	Swapping cameras or changing the tripod position to increase overlaps.
Weather conditions/ Shadow	Changing natural conditions over time (e.g. time, day, season, year), makes it difficult to re-photograph the site over time in the same condition and achieve a good result in using RP.	Phattaralerphong *et al.* 2006; Laliberte *et al.* 2007	Using a higher quality camera equipment with a good tripod and tracking multiple exposures.
Colour composite	Standard photographic format only includes Red, Green and Blue channels and uses compression bands based on the Bayer Filter where 50 % of the photos sensors are sensitive to green and 25% are sensitive to red and green.	Laliberte *et al.* 2007	Radiometric correction enhances colour issues in image processing and makes the footage appear as natural as possible.
Long-term RP	When periods are long, it is difficult to match the camera view within the photograph.	Hair 2016	Deploying GPS and using reference points of present and historical images to match the site graphically.
Brightness contrast	During a sunny day, sunlight causes plant surfaces to have bright spots (e.g. blossoms or dead standing crop) thus, the reflected rays may affect image quality.	Van Wilgen *et al.* 1996	Using a polarizing filter with high-resolution camera methodologies.
Image quality	Difficult to quantify the small plants, small flower and underestimation their significance.	Crimmins and Crimmins 2008	Using a high-resolution camera methodology and multiple image stitching.
Assess small leaves	Certain plants are very small and it is difficult to calculate leaf densities from photographs.	Chen *et al.* 2010	Using a high-resolution camera methodology.

1.4 Aim

This study aimed to develop fixed-point photography methodologies for assessing post-fire Mountain Fynbos vegetation succession as a tool for biodiversity management. This is achieved by examining biodiversity changes (species richness and abundance), phenological patterns of flowering and fruiting as well as leaf initiation, growth and senescence.

1.5 Project Objectives

The following objectives were identified:

1) Demonstrate the usefulness of a permanent photographic record of temporal changes in plant biodiversity.
2) Enhance and overcome limitations of using digital photography to provide an alternative to in-field and labour intensive sampling based on cover-abundance estimates.
3) Assess the use of phenological analysis such as flowering, fruit and growth initiation to better understand post-fire responses of fynbos plant species.
4) Develop photographic workflows to develop standardised methods for analysis and quantification of biodiversity and patterns of phenology.

1.6 Research Questions

This project included the following research questions:

1) Do species richness and the number of individual plants increases along an increasing altitude gradient in a post-burn Mountain Fynbos?
2) Do the number of species and the number of individual plants show an increase over the earlier first half of the full season?
3) Since Fynbos is defined as Mediterranean shrubland* do sites dominated by shrubs have a higher species richness than sites with less shrub abundance?
4) Does the vegetation cover change with maturity and is there a clear spring growth peak which is consistent with normal growth patterns in Mediterranean climates?
5) Can datasets of FPRP explain what is the rate of similarity between plant species richness, number of individual plants and total vegetation cover (%)?
6) Can high-resolution digital photography replace the classical phytosociological technique such as Braun-Blanquet cover-abundance estimates?

* (Moll *et al.* 1984). Is fynbos a heathland? 80. 352-355. Various definitions of both heathland and fynbos are evaluated, with the conclusion that all Cape fynbos communities are, in the broad sense, true heathlands, whatever the substrate. This definition aligns with "Heathlands and Related Shrublands: Descriptive Studies. Ecosystems of the World" 9A/9B edited by R. L. Specht (1979).

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of the Mediterranean-Type Ecosystems

Mediterranean-type ecosystems (MTEs) are the most diverse and dynamic ecosystems in the world, due to their high species richness and endemism (Cowling *et al.* 1996). There are five MTEs, namely: California, central Chile, the Mediterranean Basin, the Cape Region of South Africa, and South and south-western Australia (Simmons *et al.* 2001; Cowling *et al.* 2015; Rundel *et al.* 2016). These ecosystems have unique characteristics of possessing hot and dry summers and mild wet winters (Aschmann 1973; Rundel *et al.* 2016). This climatic regime is maintained by a wind belt shift so that the summer season is influenced by high-pressure systems causing dry conditions. During the winter season, the wind belt moves equatorward, allowing high latitude westerlies to bring winter rainfall to the region (Aschmann 1973). All west coast regions at altitudes of between 32° and 40° north and south of the equator have this reversed regime of summer drought and winter rainfall (Rundel *et al.* 2016).

Globally, the five combined regions cover a little more than 2% of the land area of the Earth (Rundel *et al.* 2016). These regions are characterized by widespread dominance of evergreen shrublands, which are dominated by species with sclerophyllous leaves (Cowling *et al.* 1996; Simmons and Cowling 1996; Dallman 1998; Cowling and Taylor 2001). The high species richness and endemism within MTEs also occur at local scales (Greuter 1994; Rovito *et al.* 2004). South African fynbos and Australian Kwongan are the MTE with the greatest plant diversities respectively (Cowling *et al.* 1996).

2.2 Overview of the Cape Floristic Region in South-Western Cape South Africa

The Cape Floristic Region (CFR) is the most distinctive and diverse of any Mediterranean region in the world, due to ecological gradients which are steep as a result of abrupt differences in altitude, soil, natural fires and climate (Goldblatt and Manning 2002). These factors combine to form an unusually large number of local habitats for plants (Rundel *et al.* 2016). The Cape Floristic Region (CFR) is located between latitudes 31º and 34º 30S in south-western South Africa (Figure 2) and covers a land area of 90 000 km^2 (Deacon 1983; Cox and Underwood 2011), which is less than one-twentieth (5%) of the land area of the southern African subcontinent (Rundel *et al.* 2016), CFR consists of a mosaic of sandstone and shale substrata with local pockets of limestone (Mitchell *et al.* 1986; Richardson *et al.* 1996).

The Cape Floristic Region (CFR) is one of the world's 36 global biodiversity hotspots(Van Wilgen *et al.* 2016), considered as the greatest non-tropical concentration of higher plant species in the world (Goldblatt and Manning 2002), known for its high endemism (Deacon 1983; Cox and Underwood 2011) and CFR has more than 9000 vascular plants, 68.7% of which are endemic, 8920 species are flowering plants of which 70% are endemic (Goldblatt and Manning 2002). Also, it has the highest concentration of South Africa's threatened taxa (65%), and taxa of conservation concern (60%) (Figure 2; Table 6); (Raimondo *et al.* 2009; Van Wilgen *et al.* 2016).

Table 6. Several plant taxa of conservation concern include threatened taxa and endemic threatened taxa in South Africa's biomes (Raimondo *et al.* 2009; Van Wilgen *et al.* 2016):

Biome	Extinct taxa	Threatened Taxa	Endemic threatened taxa	Taxa of conservation concern	Endemic taxa of conservation concern
Albany Thicket	1	70	39	144	62
Desert	1	13	1	46	4
Forest	1	94	45	189	91
Fynbos	24	1805	1745	3296	3151
Grassland	6	245	171	536	343
Indian Ocean Coastal Belt	1	75	36	134	55
Nama Karoo	1	22	10	75	40
Savanna	1	146	72	317	150
Succulents Karoo	0	288	228	668	524

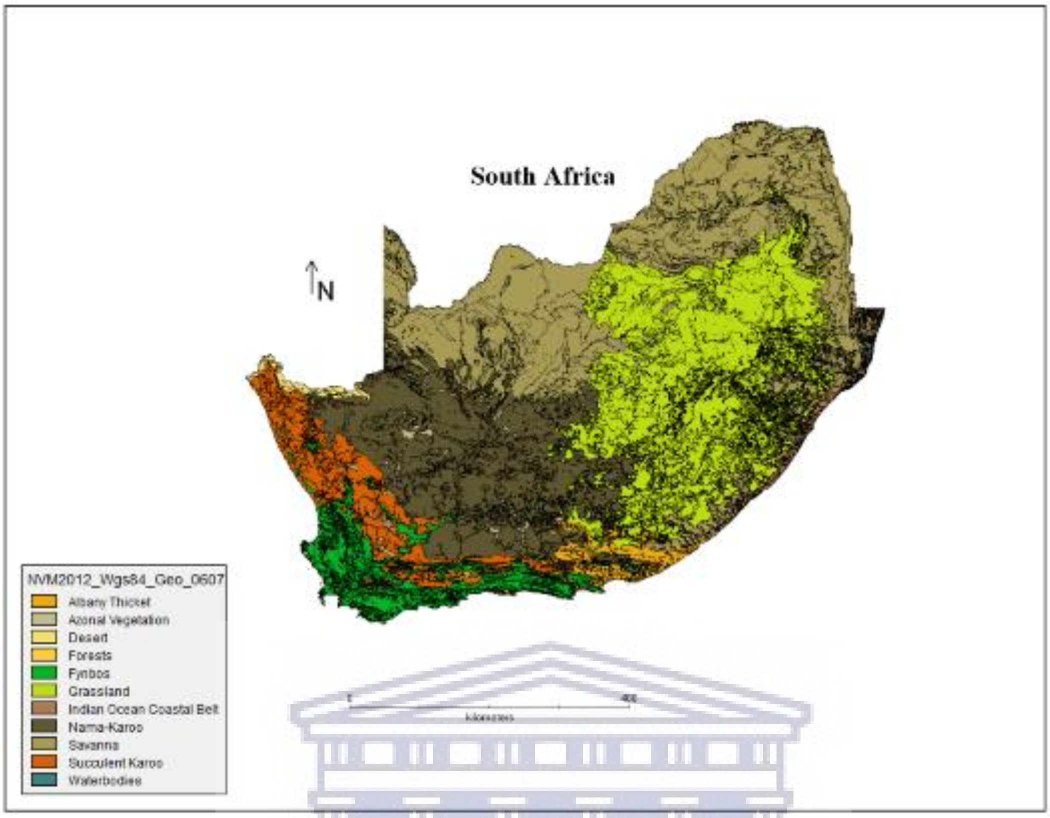

Figure 2. Map showing the distribution of the different biomes, The Cape Floristic Region (CFR) of South Africa included in the legend.

The Cape Flora is colloquially known as “Fynbos”, covers 19,227 km^2 (54%) of the CFR. Fynbos is the wide category of *sclerophyllous shrublands* or *heathland*, which are dominated by four major plant floristic groups along with the vegetation of the southwestern Cape, South Africa (Table 7), namely: *ericoids*, *proteoids*, *restioids* and geophytes groups (Bond *et al.* 1984; Moll 1990). These plant forms possess specific adaptations to cope with the summer droughts. These include thick stems and evergreen hard leathery leaves which are referred to as being sclerophyllous (Mitchell *et al.* 1986; Cowling 1990; Richardson *et al*. 1990; Archibold 1995). The Fynbos Biome has the most threatened plant taxa, which is estimated at 1805 species. It also has the most threatened endemic taxa at 1745 species, 3296 taxa of conservation, 3151 endemic taxa of conservation concern and 24 extinct (Goldblatt and Manning 2002; Raimondo *et al.* 2009; Van Wilgen *et al.* 2016).

Table 7. Characteristics of the four major plant forms of fynbos biome within the Cape Floristic Region (CFR) (Campbell 1983; Rundel *et al.* 2016):

Group name	Characteristic
Ericoids	Small-leafed shrubs reach 0.5-2 m in height, this form gives fynbos its heathlike appearance, representing many families and include more than 3000 species.
Proteoids	The *proteoids* form the tallest matrix of the fynbos community with Gondwana origins, commonly woody Proteaceae reach 2-4 m in height.
Restioids	Evergreen reed-like plants, uniquely diagnostic of fynbos, they are members of the Restionaceae and a family with origins in Gondwanaland and reaches height to a few centimetres to 3 m.
Geophytes	Prized as horticultural plants, usually most conspicuous after fires with attractive blooms, includes more than 1500 species. The Cape Region contains the highest diversity of geophytes and bulbs in the world.

2.3 Natural Fire Regimes in the Fynbos

Natural fires are an important and essential natural disturbance in the ecology of the highly flammable fynbos (Cowling *et al.* 1996; Bond and Keeley 2005). Most species in the fynbos biome rely on natural fires pre-regeneration (Cowling 1990) and have specific adaptations that include serotiny where seeds are stored in cones or inside the bracts of old flowers and are released immediately post-fire (Mutch 1970; Lamont *et al.* 1991; Keeley and Fotheringham 2000; Brown and Botha 2004).

Too frequent or too infrequent fire reduces fynbos biodiversity (Taylor 1969). Too frequent fires do not allow the mature plant to complete sufficient full flowering seasons and therefore insufficient seeds set on the canopy of the plants (Bond *et al.* 1984). Too infrequent fires cause adult parent plants to become senescent with many of the seeds held on the canopy to have become predated upon by insects or damaged by pathogens (Bond and Keeley 2005; Van Wilgen 2009). These fires allow for the recycling of nutrients and re-establishment of new species assemblages and avoid competitive dominance from becoming established (Bond and Keeley 2005; Drenovsky *et al.* 2012).

Fire seasonality and alterations in fire intensity can also influence species composition and survival in the fynbos biome (Bond and Van Wilgen 1996; Keeley 2009). Hotter and drier climates could increase the frequency and intensity of fires, and this is one of the scenarios predicted for future climate change (Forsyth and Van Wilgen 2008).

2.4 The Influence of Natural Fire Regime

Fire will burn most above-ground biomass and reduce overall vegetation cover (Keeley and Fotheringham 2000), after which a new assemblage of species will regenerate (Mutch 1970; Bond *et al.* 1984; Lamont *et al.* 1991; Midgley *et al.* 1998; Keeley and Fotheringham 2000). Post-fire succession involves a shift in the dominance of species assemblages, growth forms and the vegetation cover that will progressively increase and a turnover of different growth forms will occur (geophytes, *ericoids, restioids, proteoids* and annuals) (Powell 2013). Cowling and Pierce in 1988 found that annuals, geophytes and resprouting shrubs dominated the first year of plant succession (Cowling and Pierce 1988). In Lowland Fynbos vegetation the early successional is dominated by graminoid (grass and grass-like plants with sword-like leaves) and *restioid* growth forms (Hoffman *et al.* 1987). In Mountain Fynbos Powell (2013) observed that during recovery, *ericoid* shrubs come to dominant while *restioids* become less dominant; *proteoid* shrubs often decreases in old (>25-30 years) post-fire vegetation (Taylor 1969).

Post-fire successional processes are complex and vary considerably from site to site. Furthermore, the succession is also influenced by moisture conditions, soil characteristics, as well as by stochastic processes (Connell and Slatyer 1977; Noble and Slatyer 1980; Pickett *et al.* 1987; Thuiller *et al.* 2007). For instance, wet areas can support long-lived *restioids* species and will never support a dominance of *ericoid* shrubs (Bond and Van Wilgen 1996; Capitanio and Carcaillet 2008; Rutherford *et al.* 2011).

2.5 The Nature of Succession in Mountain Fynbos

Total vegetation cover, as well as the abundance of different species, change over time and in response to major disturbance events such as post-fire weather conditions and stochastic fire induce changes that impact species survival (Campbell 1986; Thuiller *et al*. 2007; Fisher *et al*. 2009; Driscoll *et al.* 2010; Rutherford *et al.* 2011; Van Wilgen 2012). Frequent fires may cause a decrease in the number of species and local extinction, also it affects the life cycle of some plant species such as the Proteaceae which would likely become extinct with a fire return period of shorter than five years (Gill and Bradstock 1995; Keeley 1995; Charrette *et al.* 2006; Fisher *et al.* 2009). The age at which a plant community is burned will influence the floristic and structure of the post-fire community (Higgins *et al.* 1997; Cowling and Taylor 2001; Rutherford *et al.* 2011).

The assemblage of species and structure of the plant community in fynbos is influenced by long-term changes in the environment such as rainfall, temperature, wind and atmospheric carbon concentrations regimes (Midgley *et al.* 1998; Poorter 1998; Midgley *et al.* 2003; Jacobsen *et al.* 2009). The assemblages would also be influenced by physical disturbance such as livestock browsing and fossorial rodent digging (Powell 2013).

Mountain Fynbos is mostly restricted to wetter mountainous regions (>700 mm annual rainfall), where temperature decreases are associated with an increase in the height of the mountain gradients. Species diversity is related to mountain gradients, and to the difference in weather conditions during the seasons of the year. Increased rainfall and lower temperatures are associated with increasing elevation (Goldblatt 1997), including the moisture content of the air, the amount of incoming solar radiation, cloud cover and wind regime (Brown *et al.* 2013).

Agenbag *et al.* (2008) showed that plant species diversity increased at lower altitudes (545 - 953 m), then it decreased at really high altitudes. They also reported the shifts in dominant growth forms across the gradient, where vegetation cover was dominated by low shrubs on low altitude (545 - 953 m), while on higher altitude, the dominant growth form was *graminoids*, such as (*restios, sedges* and *grasses*) (953 - 1,576 m) (Agenbag *et al.* 2008).

The Cape Floristic Region (CFR) has high plant species diversity both (alpha and beta) in terms of an altitudinal gradient and a temporal gradient (age after a fire) within Fynbos Biome (Campbell and Van der Meulen 1980). However, alpha diversity is related to the number of species in the small area, also referred to the nature of succession in fynbos vegetation more than beta diversity (Cowling 1990). The Cape Floristic Region (CFR) has high levels of alpha-diversity and appears to be particularly high in differences in species composition from one area to another (Van Wilgen *et al.* 1996), which due to the high degree of plants richness and endemism (Bond *et al.* 1984). In Mountain Fynbos, alpha diversity decreases as the height increases (Campbell and Van der Meulen 1980). Beta diversity is also high and effected by the same factors of alpha diversity as shown above, but beta diversity is referred to species turnover along environmental gradients or habitat more than to fire effect (Taylor 1978; Campbell and Van der Meulen 1980; Cowling 1990). Gamma diversity (landscape level) is related to historical processes involving the evolution of ecologically equivalent species within similar habitats over geographical gradients (Auerbach and Shmida 1987). Post-fire age can result in a high turnover of gamma diversity within two regions in fynbos communities (Werger *et al.* 1972; Campbell and Van der Meulen 1980; Cowling 1992).

2.6 Plant Phenology of Fynbos Biome in Post-Fire

Post-fire the frequency and weather conditions, season and intensity of wildfires are significant determinants of structure and composition of the Fynbos Biome assemblages (Taylor 1978) or Mountain Fynbos (Wicht 1948). Gill has categorised the regeneration of plant species into four growth forms (Table 8) with associated survival mechanisms (Gill 1981). Martin suggested that there is a relationship between the type of regeneration and life form during post-fire months, and he proposed post-fire phenological mechanisms (Table 9) (Martin 1966).

Table 8. The categorization of the regeneration categorization based on regeneration of Mountain Fynbos species of growth forms according to their survival mechanisms (Wicht 1948):

The regeneration and survival mechanisms in post-fire	Growth groups	Family examples	Plant species examples
Plants have an underground storage organ and it is first to appear after the fire or after the first season of rainfall.	Geophytes	*Amaryllidaceae*	*Cyrtanthus angustifolius*
Regrow from rootstock after a fire or being browsed down.	Sprouters	*Poaceae*	*Eragrostis capensis*
Obligate regeneration from seed. Parent plants are killed by fire or heavy browsing pressure.	Re-seeding shrubs	*Scrophulariaceae*	*Selago corymbose*
The thick bark is protected dormant stem buds from the burn.	Plants with thick bark	*Proteaceae*	*Protea cynaroides* and *Protea foliosa.*

Table 9. Martin classification of plant species of Mountain Fynbos into five phenological groups of growth forms according to their post-fire mechanisms (Martin 1966):

The regeneration and phenological mechanisms to survive in post-fire	functional groups	Family examples	Plant species examples	Reference
Producing flower heads and blooming almost immediately in post-fire without the intervention of a leafy period.	Geophytes	*Hypoxidaceae*	*Hypoxis argentea*	Pierce and Cowling 1984
Regenerate vegetatively quickly and flower about a month later than geophytes, as they mostly regenerated from rootstocks.	Suffruticose subshrubs and herbs	*Ranunculaceae* and *Asteraceae*	*Anemone caffra* and *Senecio speciosus*	Martin 1966; Pierce and Cowling 1984
Regenerate very slowly in the first year but blooming the following spring.	Some herbs and mainly woody plants	*Proteaceae* and *Celastraceae*	*Leucadendron salignum* and *Maytenus heterophylla.*	Martin 1966
Plants which begin to bloom about one month later than suffruticose subshrubs and herbs.	Vegetation is mixed. Ground growth forms.	*Euphorbiaceae* and *Poaceae*	*Euphorbia silenifolia* and *Panicum ecklonii.*	Martin 1966
Regenerated slowly from seed from October to the late summer.	Plants which are destroyed by burning	*Rosaceae*	*Cliffortia graminea*	Pierce and Cowling 1984

Few studies have investigated the phenology and plant life cycles in South Africa. Such studies exist for Namaqualand (Van Rooyen *et al.* 1979), the southern region (Bond 1980), the southwestern region of the biome (Kruger *et al.* 2012), the South-eastern Cape (Pierce and Cowling 1984) and the Eastern Cape (Palmer and Lubke 1982). Some studies showed that many annual species regenerated from dormant seeds surviving a fire in the soil (Sweeney 1956). However, there is a poor representation of annual species in post-fire in Fynbos (Adamson 1938)

The monitoring studies of Pierce and Cowling (1984) found there are significant increases by 8, 43% of some perennial shrubs species include *Solanum retrofiexum*, *Geranium ornithopodum*, the exotic trees *Acacia longifolia* and *Pinus pinaster* regenerated from the seed during a 13 month 1980-1981 period of post-fire. However, Martin observed that some species of *Erica spp*. regenerate solely from seed that is wind disposed of up to two years of post-fire (Martin 1966). Werger *et al.* found some perennial species regenerating from comprising the basal cover of the plant species (Werger *et al.* 1972).

2.6.1 Changes of Cover Abundance and Species Composition in Post-Fire Fynbos Vegetation Succession

Regeneration in the Fynbos Biome is a continuous process and that the increase in the percentage of vegetation cover is related to the patterns of seasonal rainfall (Durand 1990). Pierce and Cowling (1984) showed that over time the increase in the percentage vegetation cover is rapid during wet seasons and slows during the drought seasons (Werger *et al.* 1972). Gill stated that nutrient qualities in ash might influence the regeneration of some species post-fire (Gill 1981).

Pierce and Cowling 1984 observed most of the *dicotyledonous* plants e.g *Fabaceae* and *Asteraceae* increased in density, whereas the *sedges* and *grasses* did not show significant increases, although these plants increased their coverage in the Fynbos community during post-fire.

Wicht 1948 observed that geophytes after rainfall had accelerated to grow and develop foliage. Further, most succulents grew during autumn (Holland *et al.* 1977; Pierce and Cowling 1984). Pierce and Cowling (1984) observed that most growth patterns of *restioids* and *grass* species occurred in the cool, wet seasons (spring to summer), *restioid* and *graminoid* species were fastest to regenerate post-fire, and temporarily dominated the plant cover but with time shrubs and sprouting herbs become more dominate (Pierce and Cowling 1984). On another hand, some species of *restioids* were also observed to grow during summer (Pierce and Cowling 1984; Bond and Keeley 2005).

In summer, most Fynbos species especially shrubs tended to lose their leaves during drought, due to low soil moisture (Frankie *et al.* 1974; Kummerow 1983; Pierce and Cowling 1984). Small-leaved *sclerophyll* shrubs grew throughout the year and showed increased vegetation cover during summer (Bond 1980; Pierce and Cowling 1984). Subtropical large-leaved *sclerophyll* shrubs showed irregular growth and reproduction from summer to autumn, many of the woody species of *Ericaceae* showed a continued in growth during summer and increasing heights (Pierce and Cowling 1984)

Pierce and Cowling in 1984 observed some plant species such as herbs (*Cynoglossum enerve),* geophytes *(Bobartia macrocarpa) and grasses (Pteridium aquilinum)* were the tallest plants in the landscape in the early post-burn phases. Also, he monitored some species such as *Cynoglossum enerve* and *Pteridium aquilinum* that had finished their growth stage and died back to ground level.

2.6.2 Leaf Development and Flower Phenology

To analyse the phenological patterns, many previous studies used direct observation to qualitatively assess seasonal and annual changes (Williams 1971; Dickinson and Dodd 1976; Pierce and Cowling 1984). Pierce and Cowling 1984 grouped species phenological patterns into growth forms (annuals, geophytes, *restioids*, succulentss and grasses). They also defined plant species in terms of the height of perennation buds, leaf size and photosynthetic mode data and observed over two seasons (Raunkiaer 1934; Pierce and Cowling 1984). Furthermore, they recorded aspect of the life cycle of plants growth, that included shoot elongation, leaf development, leaf yellowing, before and including abscission, flowering phenology such as (pre-flowering "bud" and full flowering "open flower", unripe and ripe fruiting/ seeding) (Pierce and Cowling 1984).

Their results showed that different substrates (soil type) had a minimal effect on phenophases (Campbell 1983). Pierce and Cowling 1984 had observed that many plant species (*Seneciospeciosus, Cyrtanthus angustifolius and Gerbera viridifolia*) stimulated to bloom profusely following afire.

Almost all annuals started to grow and bloomed from autumn to spring. Some species of geophytes such as *Cyrtanthus angustifolius* flowered after two days of the first rainfall of post-fire (Pierce and Cowling 1984). Pierce and Cowling 1984 observed the initiation of leaf growth of geophytes species from autumn to spring (Heddle and Specht 1975; Kruger *et al.* 2012). They also found geophytes blooming peapod in spring and continued at intermittent intervals through winter (Pierce and Cowling 1984).

CHAPTER 3: DESCRIPTION OF STUDY AREA

3.1 Geographical Location

This study was located in Silvermine Nature Reserve (SNR), Cape Peninsula, South Africa (latitude -34.0869; longitude 18.4206 and height 310m) (Figure 3). It forms part of the TMNP, which is administered by SANParks. The Silvermine Nature Reserve (SNR) is located in the southern section of Table Mountain National Park (TMNP), stretching from Kalk Bay in the south through to Constantiaberg in the north and it is surrounded by the suburbs of Constantia, Tokai, Lakeside, Muizenberg, St James, Kalk Bay, Fish Hoek, Noordhoek and includes the catchment of the Silvermine River (Figure 4).

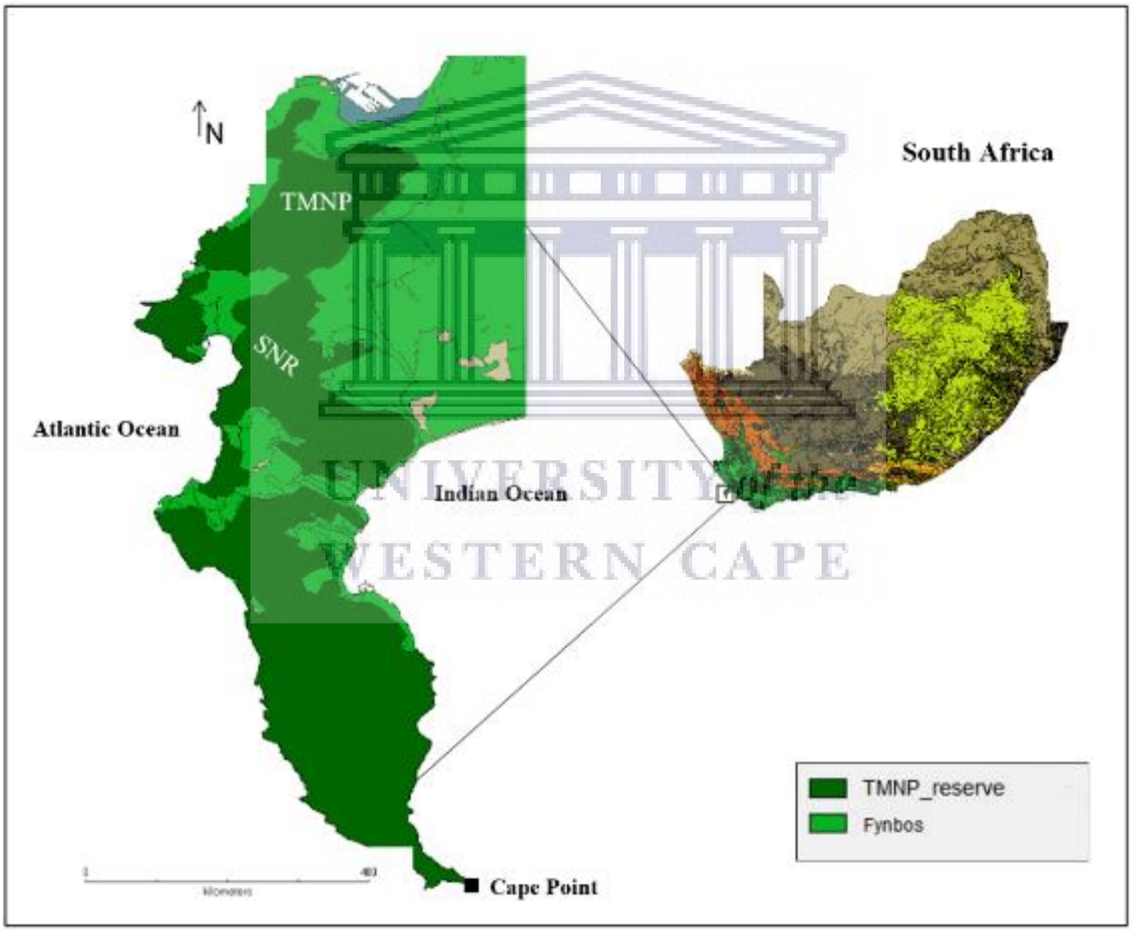

Figure 3. The location of Silvermine Nature Reserve (SNR) within the Cape Peninsula, and which forms part of the Table Mountain National Park (TMNP), South Africa.

Figure 4. Key landmarks within and close to the study area inside Silvermine Nature Reserve (SNR), which forms part of the Cape Peninsula. Image based on Google Earth imagery.

3.2 Overview of Historical Background of the Silvermine Nature Reserve (SNR)

Based on Palaeolithic artefacts, human occupation of the SNR dates back to 120,000-160,000 years ago (Deacon 1983; Scally *et al.* 2012; Dzingwe 2019). For at least the past 100, 000 years the fynbos landscape has been subjected to anthropogenic fires regimes (Deacon 1983; Hall 1984).

The Silvermine Nature Reserve (SNR) catchment has been populated for approximately 16,000 years, and these people impacted the landscape with frequent habitat burning (Dzingwe 2019). The Fynbos Biome become further impacted by Dutch colonialists who arrived in the Cape in 1652 and developed settled agriculture (Naidoo 2016). Dutch thought these mountains contained silver and excavation of mines occurred from 1675 to 1685. However, no silver was ever found but the name continues to this day (Malan *et al.* 2015; Dzingwe 2019).

In 1902, the SNR officially became a forest reserve, covering 472 hectares and included areas up to the current Tokai Forest Reserve (Cilliers 2002). From 1905 to the 1960's the alien forest trees (e.g. *Pinus radiata*) were planted throughout this area (Ashton 1985; Dzingwe 2019). The current distribution of invasive vegetation within the SNR reflects the past intentional planting of these invasive species (*especially A. melanoxylon, A. saligna, A. melanoxylon* and *P.*

pinaster) (Ashton 1985). In 1950 the Council of the City of Cape Town embarked on a policy to remove alien plants from Table Mountain and SNR (Cilliers 2002).

On 16 January 2000, two major fires burned much of the Southern Cape Peninsula Mountain Chain (Euston-Brown 2000; Kruger *et al.* 2000; Scott *et al.* 2000; Pooley 2010). Due to favourable weather conditions (drought wind), the intensities of the fires were especially high (reaching 10 000 to 40 000 kW/min) areas of introduced species and plantations (Scott *et al.* 2000; Cilliers 2002; Pooley 2014); damaging 200 shacks and 70 houses (Pooley 2011).

Fifteen years later, three separate fires raged in the Western Cape Peninsula in March 2015 (Songelwa *et al.* 2015). These were referred to as the Cape Point fire, the Muizenberg fire and the Scarborough fire (Wikipedia 2020). These fires started in the Muizenberg section in the evening and due to the strong winds, coupled with very hot and dry conditions, quickly spread across Tokai forest to the SNR and then onto Noordhoek and towards Chapman's Peak Drive and finally reached Scarborough on the Atlantic coast (Songelwa *et al*. 2015; Wikipedia 2020). The Muizenberg fire burned 5,120 ha of forest and fynbos burnt along with several buildings and other infrastructure (Wikipedia 2020). As a consequence of the 2015 fires, much of the SNR was burnt including the tented camp and boardwalk around the Silvermine dam (Songelwa *et al.* 2015; Wikipedia 2020).

3.3 Geology and Soils

The Silvermine Nature Reserve (SNR) is characterized by rocky acidic soil derived from Ordovician sandstones of the Table Mountain Group. The soil is coarse quarzitic sands and has low-nutrient properties, and is usually dry or wet or acidic (Mitchell *et al.* 1986; Richardson *et al.* 1996; Cox and Underwood 2011). The soil is shallow or near deep and often consists of imperfectly weathered rock fragments such as lithosols, which are characteristic of Mountain Fynbos landscapes (Cilliers *et al.* 2005; Bowman *et al.* 2012; Dzingwe 2019). The deep soils are organically rich, moist and usually colluvial (defined as loose, unconsolidated sediments), and occur in wetter land above the Silvermine dam and at the higher section of the Silvermine River (Cilliers 2002; Cilliers *et al.* 2005; Dzingwe 2019).

On lower slopes around the dam, there are deep mixed soils that are formed by colluvial accumulations of sandstone debris and are intermixed with finer material, rocks and sands, including dunes which are formed from sands mixed with the colluvial deposits (Cilliers 2002; Dzingwe 2019). In the geologically recent dunes that formed in the lower Fish Hoek-

Noordhoek valley, the substrates are rich in carbonates that originated from weathered seashells. These soils are relatively unstable and sensitive to disturbance and invasion by alien species (Koop *et al.* 1982; Cilliers 2002; Cilliers *et al.* 2005; Bowman *et al.* 2012).

3.4 Climate

The Silvermine Nature Reserve (SNR) experiences a typical Mediterranean-type climate, characterised by dry summers, and mild wet winters (Aschmann 1973; Forsyth and Van Wilgen 2008; Rundel and Cowling 2013). Rainfall in the Cape Peninsula is cyclic and orographic, with the highest rainfall occurring from June to August. Snow is a very rare occurrence in the Cape Peninsula Mountains. Prevailing summer winds blow from the south and southeast direction. These winds blow along the shore generating an upwelling of cool sea temperatures and an off-shore high-pressure cell. These cool sea temperatures and a land-sea breeze circulation contribute to characteristic mists. There is also significant cloud-induced moisture at higher altitudes of the Peninsula Mountain Chain.

Weather conditions during the study period of 2016 are summarized in Figure 5. The total average rainfall (annual or seasonal) was 50 mm, while June 2016 was the wettest month, and November 2016 was the driest month. Monthly average temperatures ranged between 6.4 to 28 °C, while July 2016 was the coldest month and January 2016 was the hottest month (Figure 5).

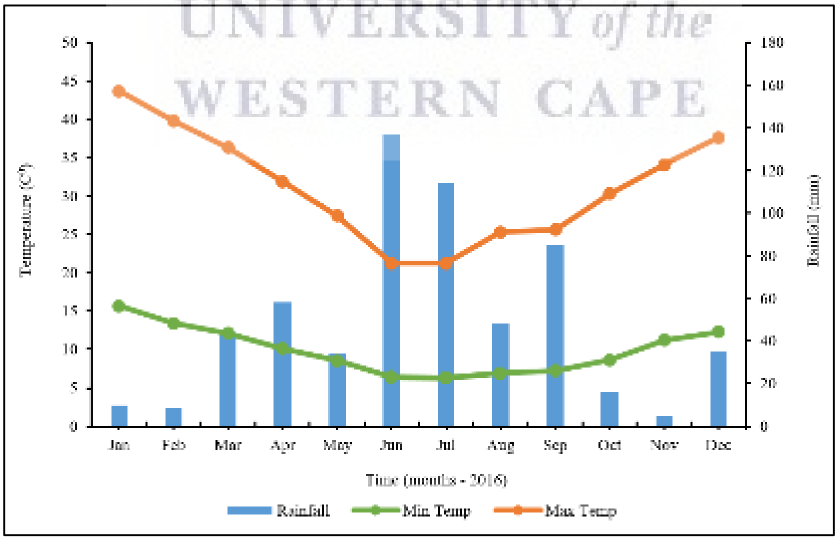

Figure 5. Climate diagram for study the sites in the Silvermine Nature Resave SNR showing the average monthly rainfall (mm), as obtained from the climate station data (0004695 X-SILVERMINE NATURE RESERVE). The average daily (maximum – minimum) temperature (^{0}C) are extracted from the climate station data (0020780 4 - KIRSTENBOSCH). All the climate station data was measured at 08:00.

3.5 Vegetation

The main vegetation community within SNR is classified as Mountain Fynbos (Figures 2, 3 and 6) (Cowling 1990), and is restricted to highly leached, acidic, quarzitic nutrient-poor soils (Van Wilgen *et al.* 2016).

The Silvermine Nature Resave (SNR) has high plant diversity and represented by Scrophulariaceae Juss lazy bush (Eng.); koekblommetjiesbos, sukkelbossie (Afr.), *Nemesia fruticans*, *Iridaceae*, *Helderberg Painted Lady*, *Santalaceae Thesium litoreum Brenan*, *Fabaceae*, *Aspalathus L* and *Helichrysum*, *Helichrysum dasyanthum* (Kruger 1979; Cilliers 2002; Jayiya *et al.* 2004; Cilliers *et al.* 2005; Bowman *et al.* 2012; Dzingwe 2019). The following species in the forms: *Ericaceae*, *Erica hirtiflora*, *Erica lutea* and *Erica baccans* are common (Kruger 1979; Jayiya *et al.* 2004; Dzingwe 2019). These species range from the dry northern cliffs to moist, dense, tall *Proteoid* Fynbos in the wetter areas within the Peninsula Sandstone Fynbos as well as in the SNR (Rebelo *et al.* 2006). The steeper north-facing cliffs in Cape Peninsula such as dry *Asteraceous spp*. dominated while *Ericaceous* occur on again higher altitude or steeper. *Restio* marshes are found at the higher altitudes while the *Proteoid* common *Sugarbush* thrives on sandy soils on lower slopes (Kruger 1979; Rebelo *et al.* 2006).

Figure 6. Landscape photograph showing representative plant communities occurring in the Silvermine Nature Reserve (SNR), Cape Peninsula. This photo was taken two years after recovery from the fires of February 2015.

CHAPTER 4: MATERIALS AND METHODS

4.1 Site Selection

Five study sites were selected in recently burnt Mountain Fynbos at SNR (Figure 7 A), and all sites were located adjacent to the hiking path of the SNR so as avoid any unnecessary resampling on sensitive recovering post-fire vegetation (Figure 8). These five study sites traversed an elevation gradient of 166 m and across a horizontal distance of 2030 m (Table 10). Sampling was undertaken one year after the fires of February 2015, which represented autumn 2016 and ended by late summer 2017, and was replicated five times to represent the seasonal differences (Figure 7 B).

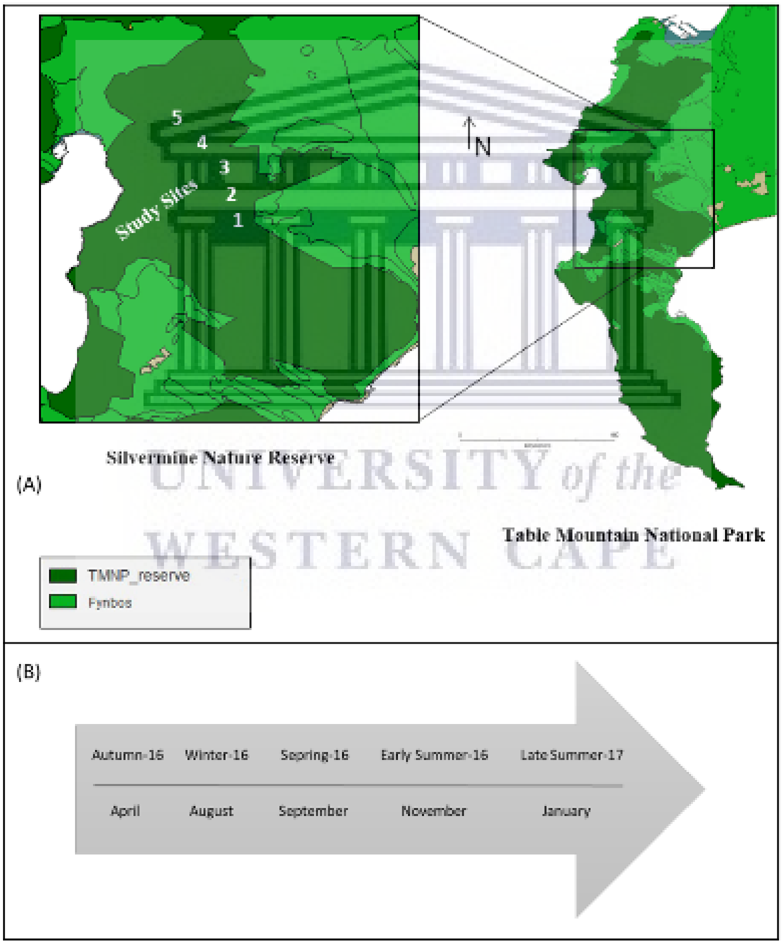

Figure 7. (A) Silvermine Nature Reserve (SNR), which forms part of The Table Mountain National Park (TMNP), five sites arranged along an altitudinal gradient of 166 m and a horizontal distance of 2030 m. (B) vegetation monitoring started from autumn 2016 and ended by late summer 2017, through five post-fire months to represent the seasonal differences for phytosociological assessment in plant communities within SNR.

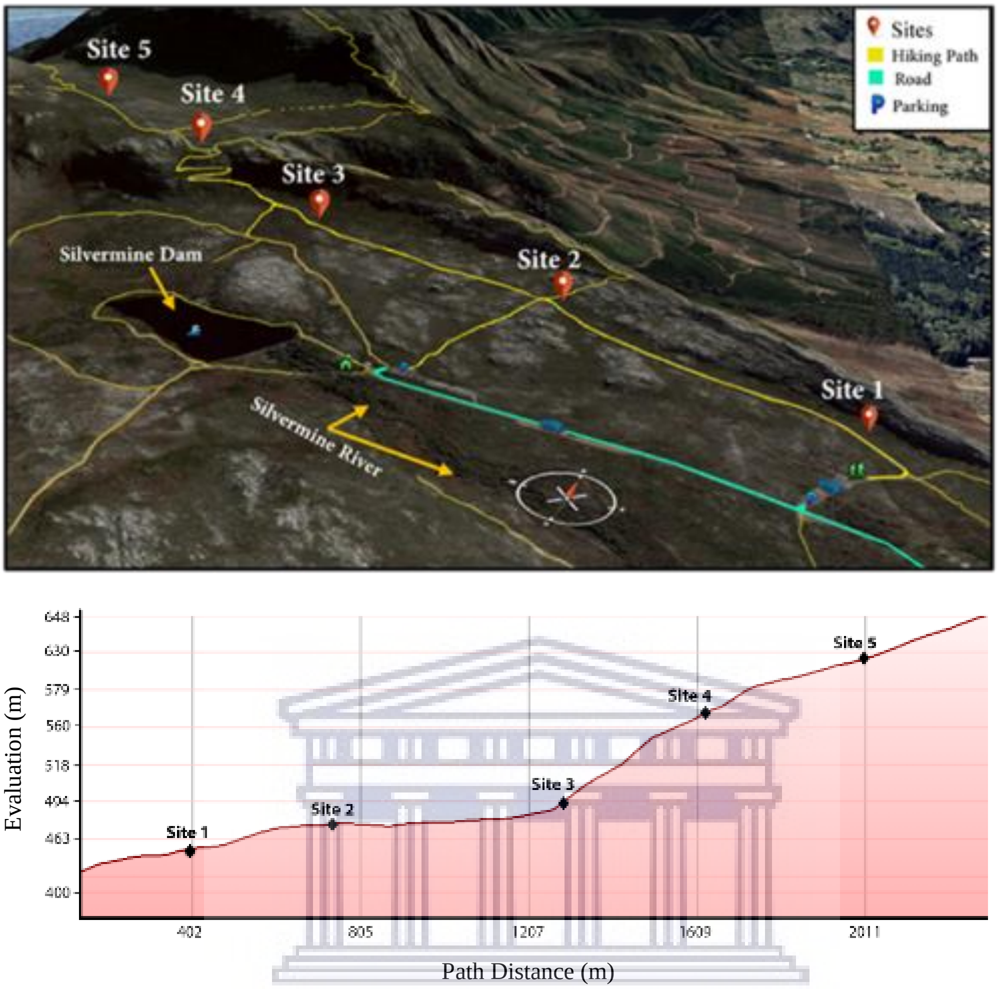

Figure 8. The altitudinal profile showing the location for each sample site across a horizontal distance of 2 030 m and a vertical climb of 166 m in Silvermine Nature Reserve (SNR). Image obtained from Google Earth.

Table 10. Precise distance and altitudes between five sampling sites located in Silvermine Nature Reserve (SNR) within Table Mountain National Park (TMNP). The longitudes and latitudes were determined by a Garmin GPS whereas the altitude was determined from Google Earth.

Study Sites	Distance (m)	Longitude	Latitude	Altitude (m)
Site 1	0	18.404620	-34.076820	460
Site 2	460	18.402610	-34.073340	490
Site 3	1.106	18.397340	-34.070500	493
Site 4	1.509	18.393330	-34.068100	565
Site 5	2.030	18.388730	-34.065420	626

4.2 Field Plot Design

Because of the high species, diversity within Fynbos Biome (Deacon 1983; Van Wilgen *et al.* 1996; Cox and Underwood 2011) to evaluate fynbos vegetation patterns (Taylor 1969; Hoffman and Cowling 1990; Mustart *et al.* 1993; Privett 1998; Hoffman *et al.* 2010; Rohde and Hoffman 2012; Powell 2013; Emms 2013) usually requires the use of a small quadrats (2 x 2 m; 2 x 4 m and 4 x 4 m) (Mustart *et al.* 1993; Emms 2013). I used similarly small quadrat to analyse phenological patterns in plant communities (e.g. leaf development, leaf initiation and condition, flowering and seed production) as well as annual cycles of plant health by using FPRP within Mountain Fynbos.

At each site, a standardised procedure for taking images was developed after several trials and error iterations (Figure 9). A quadrat size of 3 m by 2 m was chosen which is smaller than the usual 5 m x 10 m quadrats used in Mountain Fynbos; this made the assessment easier (Mustart *et al.* 1993; Elzinga *et al.* 1998; Warmink 2007; Straatsma *et al.* 2008; Bring 2009). The camera distance to the plot was fixed at 4 m and the tripod was positioned 1.6 m above the ground. The tripod was placed inside a measured 2 m x 2 m quadrants to ensure the angles of view concerning the quadrat were maintained constant (Figure 9). To process the imagery using photogrammetric methods the quadrat was further divided into six one-meter square sub-quadrats (Figures 9 and 10). Then each 1 m x 1m sub-grid was further divided into four quadrants each 500 mm x 500 mm in size, and given a reference number (Figure 10).

Six colour calibration boards (red, green and blue) were used for colour correction (radiometric correction), three were located in the back and three in the front of the quadrat. During post-production red, green and blue (RGB) of the image was compared and adjusted using these boards for the overlay radiometric colours of the image (Figures 9 and 10).

To determine vegetation height and growth rates over the season, seven measuring poles (three 1000 mm in height and four 500 mm in height) were positioned within the quadrat in a standardised pattern (Figure 10). The 500 mm poles were located in the outer left and outer right rows and the three remaining measuring poles were placed in the middle of the plot and the other poles at the back corners of the plot (Figures 9 and 10).

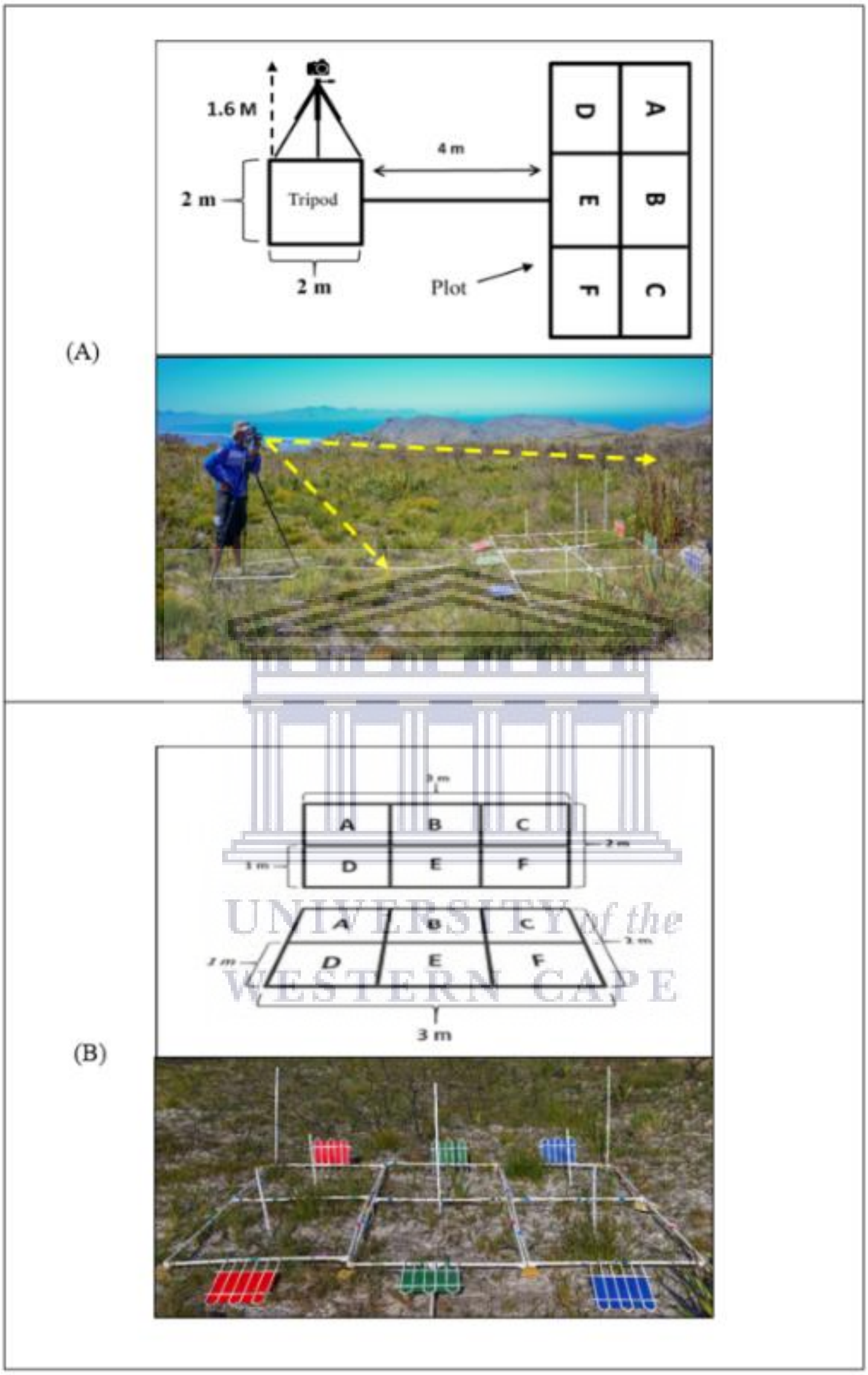

Figure 9. Field plot design for post-burn assessment Mountain Fynbos along an altitudinal gradient sites at Silvermine Nature Reserve (SNR). (A) the viewing distance between the camera to the quadrat and the height of camera above the ground. (B) quadrat size including colour calibration boards and measurement height poles.

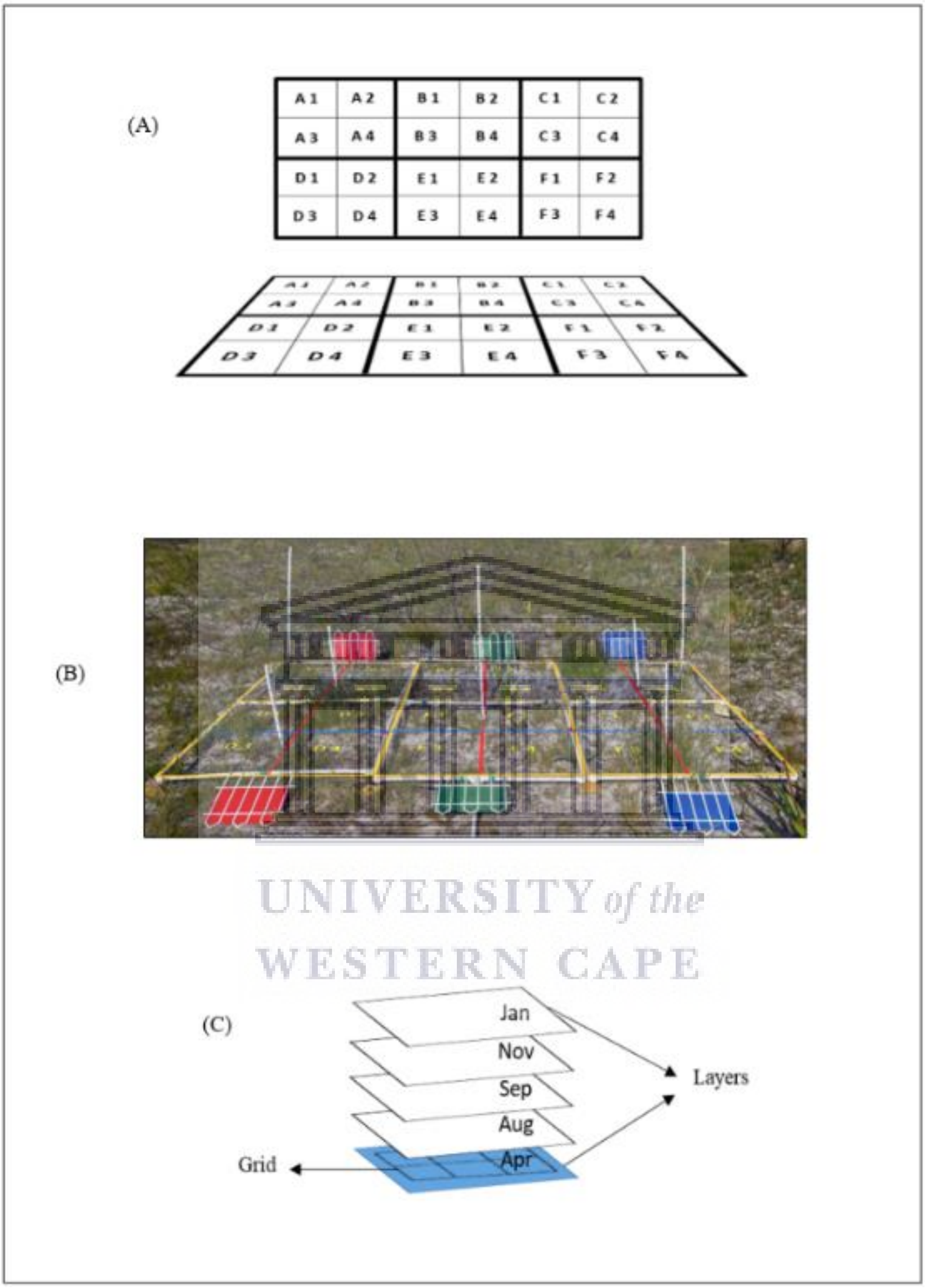

Figure 10. Sampling and analysis scheme at each of the five study sites. (A) grid with the digital reference system. (B) grid laid over quadrat of photo. (C) photo with grid and other repeat photos of following seasons were overlayed onto the grid.

4.3 Camera Specification and Operation

4.3.1 Camera and Lens Specification

For my FPP I used a Canon 5DS R high-resolution digital camera and the camera body specifications are summarised in Table 11. A Cannon 45 mm Tilt-Shift Lens was used for creating high-definition parallel panoramic imagery (Figure 11).

Table 11. Specifications of Canon 5DS R camera (Full-frame DSR) (Brawley *et al.* 2015):

Parameters	**Values**
Full model name	Canon EOS 5DS R
Resolution	50.60 Megapixels
Sensor size	Full frame 35mm (36 x 24 mm)
Viewfinder	Optical / LCD
Native ISO	100 - 6400
Extended ISO	50 - 12,800
Shutter	1/8000 - 30 seconds
Dimensions	6.0 x 4.6 x 3.0 in. (152 x 116 x 76 mm)
Availability	06/2015

The Tilt-Shift lens (Canon TS-E 45mm f/2.8) is a standard-length manual focus lens for EF mount cameras with a 51° diagonal angle of view on full-frame cameras (Greengo 2014). The Tilt function allows the lens angle to be changed relative to the image sensor and can thereby improve or exaggerate errors of distortion. In this study, I reduced the distortion of the sampling quadrat relative to the image sensor. To create a parallel panoramic image and increase the field of view, the shift function was used horizontally to capture the maximum number of horizontal pixels (Figure 11). The lenses shift facility allows the lens to be moved sideways and captured three images (Figure 11).

When photographing vegetation, there were significant sunlight reflections and glare from leaf surfaces. Consequently, I used the Hoya 72 mm NXT Circular polarizing filter to reduce these bright spots (Matiash 2015). The major distinctive of using the polarizing filter is to absorb much of the light reflections and clears up haze in distant landscapes, which provides more saturated, vivid colours, helps to boost the colours and contrast within captured images (Matiash 2015).

To increase the amount of overlap and keeping the camera at the same level for creating optimal panorama imagery (Picker 2014; Izzy 2015), I used a Triple 3 Axis Bubble Spirit Level (Figure 11).

4.3.2 Camera Operation

Five sites were re-photographed during the different seasons on a sunny day and restricted to between 11h00 and 14h00 hours. Photographs were taken only when the wind speed was less than 10 km/h. The camera was operated systematically across these sites (Table 12). The plots and camera were positioned with the sun overhead, to reduce the number of shadows while taking pictures.

Table 12. Camera setting used to increase the ability for an image to be compared over different seasons:

Parameters	**Values**
Camera mode	Manual (M)
Exposure (speed)	1/180
White balance	Daylight
Image type	RAW format with quality 50M of size (8688 x 5792 pixels)
Aperture-priority mode	(f/8)
ISO speed	100
Picture style	Auto
Auto lighter optimizer	Standard
Mirror lockup	Enable
Drive mode	Self-timer:2sec/remote.

4.4 Parallel Photography (PP)

The Parallel Photography (PP) method has been used as a tool in many studies to describe vegetation and its relationship to the landscapes (Warmink 2007; Straatsma *et al.* 2008; Bring 2009). However, in this study, PP methodology was developed by using a high-resolution camera (Canon 5DS R) with Tilt-Shift Lens (Canon 45mm f/2.8) to create high-definition panoramic imagery (Figures 12 and 13). Instead of moving the camera sideways as shown in previous studies, within this approach, the camera was fixed horizontally on the tripod (Figure 9), while the shift function built into the lens was moved sideways to capture three images, (Figure 11).

The main advantage of using a Tilt-Shift lens is that by sliding the lens to each of the furthest points, plus taking a middle photo, the three images will stitch with the least amount of artefacts. Stitching images will increase the field of view and obtaining panoramic images artefacts (Greengo 2014).

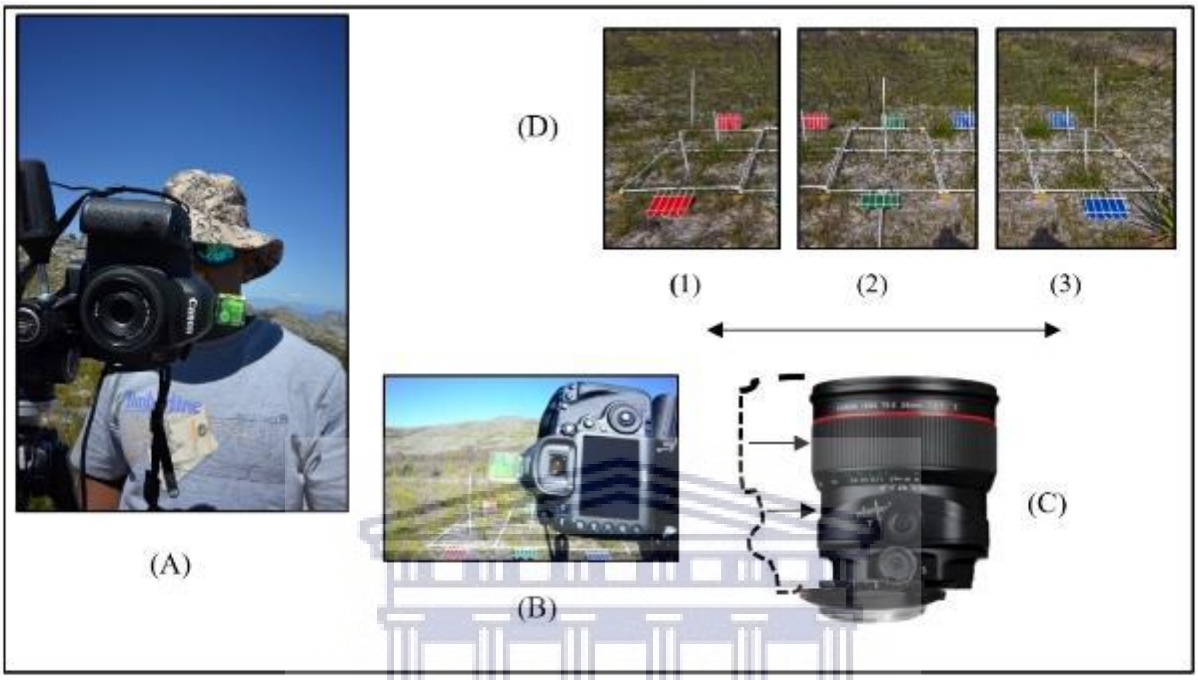

Figure 11. Operation of the Canon 5DS R with the Canon 45 mm Tilt-Shift lens. (A, B) the camera tilted into portrait mode, camera mirror lockup, a remote cable release and Triple 3 Axis Bubble Spirit Level were engaged. (C, D) three photographs were taken by the shifting the lens from photo (1) to photo (3).

4.5 Image Processing and Image Stitching

4.5.1 Image Stitching

Each of the three individual RAW images (8688 x 5792 pixels) were stitched together into a panoramic image (Figure 12), using the Photo Merge tool in Adobe Lightroom 6 (2015) (Evening 2015). Using this method an image with a resolution of (11092 x 8565 pixels) was generated with a significantly higher pixel resolution than platforms such as 8K Fulldome 8192 x 8192 (Figure 13).

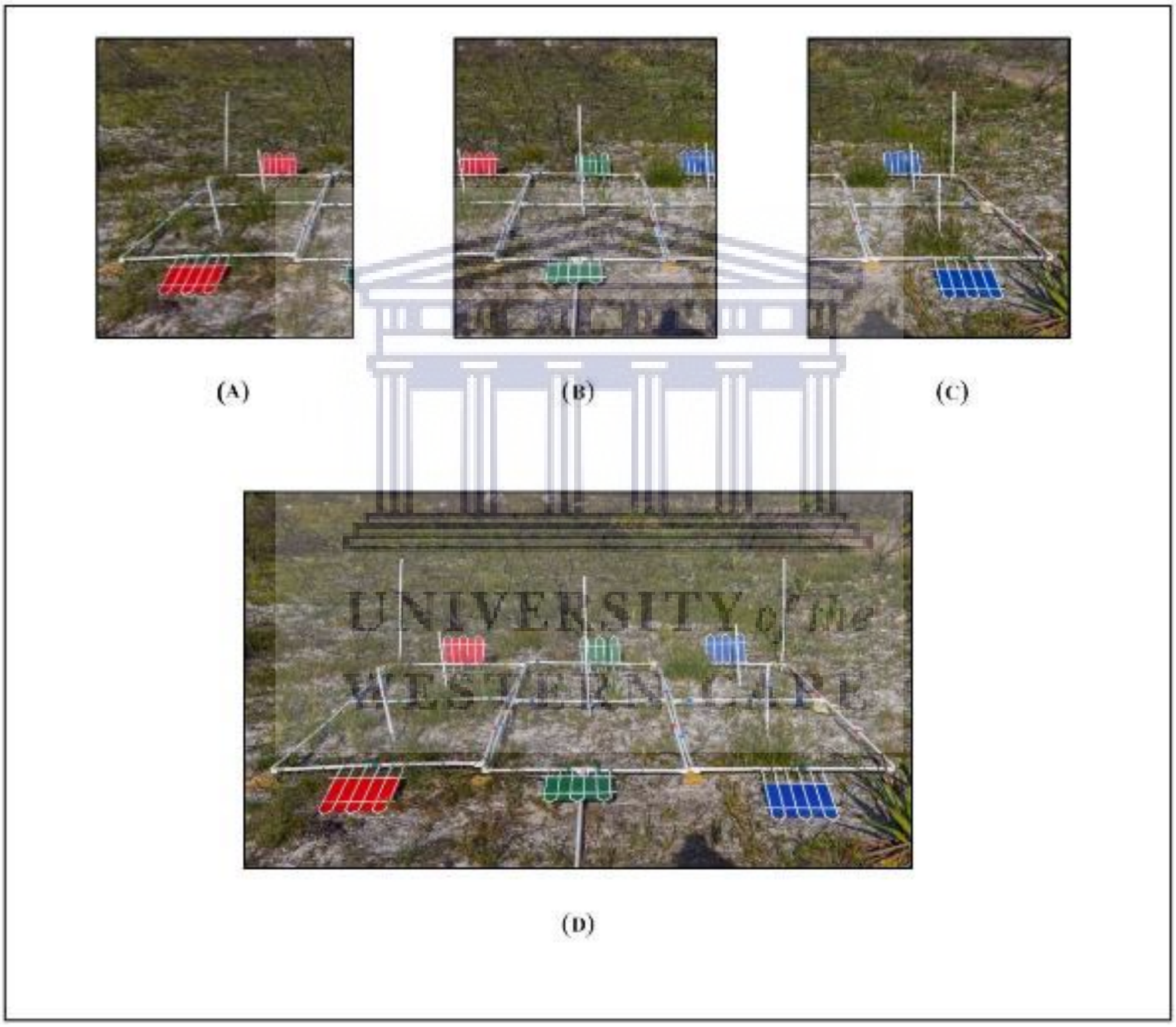

Figure 12. (A; B and C) Three individual photographs were taken at the study site by shifting the lens to produce. (D) The final stitched panoramic image.

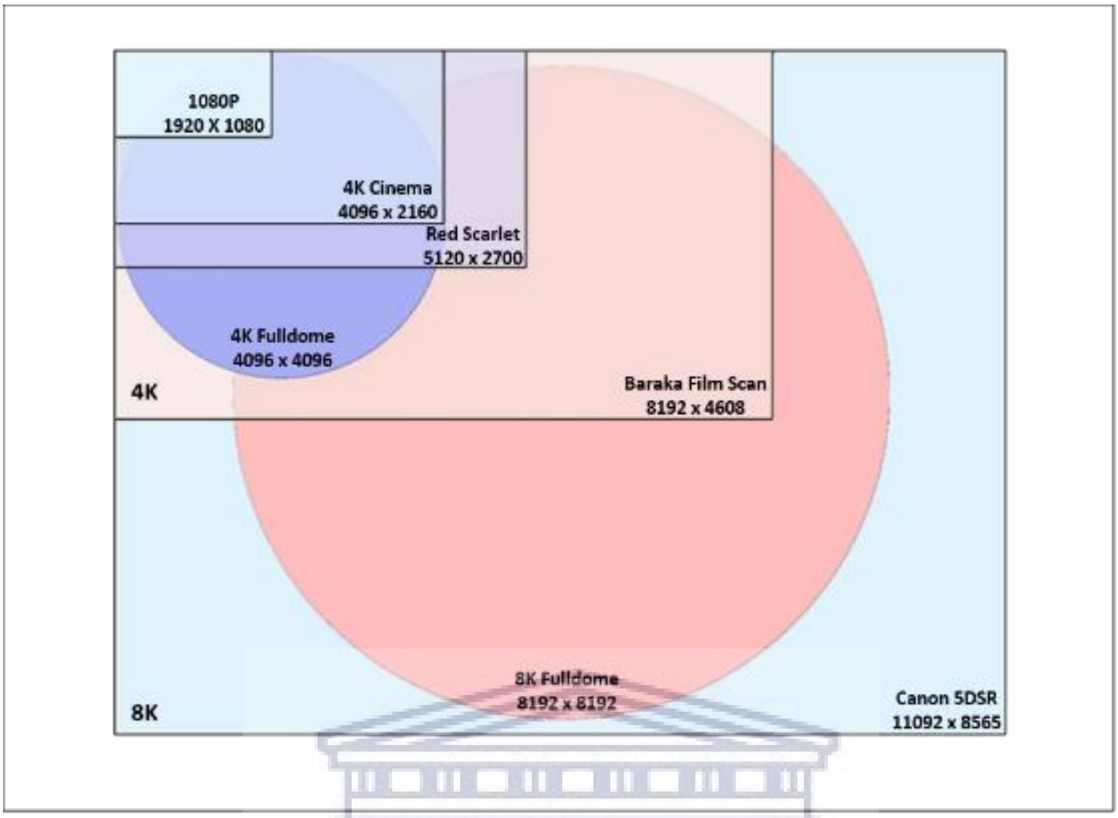

Figure 13. The final image resolution achieved from the stitched three portrait images taken with the Canon 5DS R compared against various standard video formats.

4.5.2 Colour Correction (Radiometric Correction)

Due to natural light being variable and dependant on the time of day, season and degree of cloudiness, it was important to be able to correct the reflectance values of each RGB colour channel in post-photographic processing corrections. To reduce the amount of colour correction, photographs were taken between 11h00 and 14h00 hours, and only under conditions of less than 1% cloud cover. This allowed the photographs to be stitched together in post-processing with minimal variance. To minimize the proportion of shadows, quadrat and camera were positioned in the direction of the sunlight to keep the sun overhead.

The sampling quadrats were provided with RGB boards (Figures 9 and 10), so that colour calibration could be undertaken to all images to achieve near-identical colour curves and matched exposure. The match colour tool was used in Photoshop CC 2014 to match (8 bit) of RGB colours channels between multiple images (Evening 2014).

The stitched images were converted from RAW format to Tagged Image File Format (TIFF) format (Figure 12) (Brown 2008). Tagged Image File Format (TIFF) is best for any bitmap images, which flexible and widely supported raster formats for the use in image processing, that intend to edit digital images in a working storage format and preserve image quality in a working storage format (Larson and Ward 1998; Lukina *et al.* 1999; Brown 2008; Parulski and Reisch 2009).

I hoped to construct the full dynamic range of high-contrast scene imagery by capturing the scene in different exposure bracketing, starting from the middle exposure, overexposed and underexposed and then combined them by using software that supports HDR such as PhotoMatix scores highly over Photoshop in this regard (Debevec 2008; Cohen *et al.* 2001; Brown 2006; Cox and Booth 2009). However, the smallest amount of wind caused the leaves of plants to move during data collection, so over the image processing, I was not able to merge the different exposure images. Additionally, there remains the issue of lost detail in shadowed and bright spots. Consequently, I use a method called "HDR Toning" to fix these issues (Evening 2014), which simply enhances detail in shadows and bright spots (Figure 14).

Colour adjustments and image editing were done using the Panels tools found in the Develop Module in Adobe Lightroom 6 (Table 13). The 8-bit RGB colour channels had transformed into Hue, Saturation and Luminosity (HSL) (Evening 2015). The benefits of using Colour adjustments were to increase or decrease and balance the RGB values as close to each other images as possible for the images with HDR scene, also to improve the rendering of warm the tones and adds a little bit of contrast (Evening 2015; Morganti 2015a).

Table 13. Benefits achieved during post-processing of digital images by using tool panels in the Develop Module in Lightroom 6 (Evening 2015):

Panels	**Benefits achieved during post-processing**	**Reference**
The Basic Panel	Correct the exposure for both shadows and highlights so that was good to move on to more advanced editing.	Gregory 2015
The Detail Panel	Enhance the digital images by sharpening and reducing noise.	Morganti 2015a
The Lens Corrections Panel	Correct the various optical issues on lenses such as (chromatic aberration, distortion, perspective correction “non-destructively” and vignetting).	Morganti 2015b
Camera Calibration Panel	Adjusting HSL of RGB colour channels by using the value of RGB colour boards as ColorChecker to adjust the colour value.	Morganti 2017

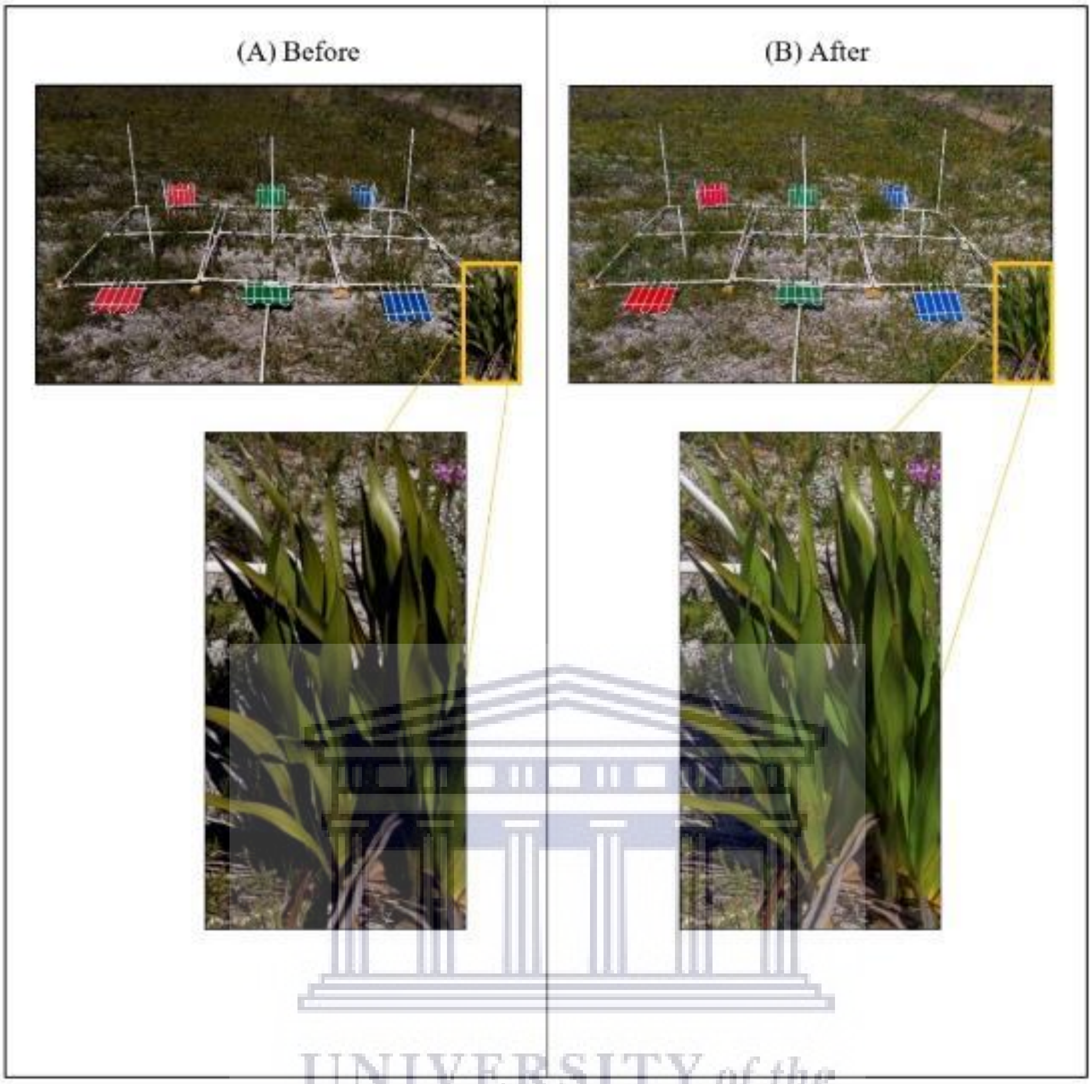

Figure 14. Image re-processing of colour correction (radiometric colour correction). (A) shows the original photo before image processing, (B) shows the final image achieved after colour correction applied in Adobe Lightroom and Photoshop.

4.5.3 Re-projection of Images

Although precautions were taken so that the distance and the angle of the photographs were taken relative to the sampling plot, re-projection is still needed to match the images of seasonal differences to each other (from April 2016 to January 2017). Geometric correction used for eliminating the geometric distortion and matching several pictures captured at different times (day or month or year) of the same object to inspect changes in the landscapes (Dijkstra 1994).

However, these images were loaded into Photoshop CC 2014 as a grid and manually rubber-sheeted to match each other by using Puppet Warp, Perspective Warp and Transform tools (Evening 2014). The geometric correction was done in Photoshop CC 2014. This correction was used to eliminate the geometric distortion that occurs when an image is captured (Figure 10), and also to match two different images from the same object (Sonka *et al.* 2008). The repeat photographs of each study site were matched by using Photoshop CC 2014 (Powell 2013; Emms 2013). This method was developed by using a grid with the digital reference system prepared in PowerPoint. Each plot was divided into four small grids (1 x 1 m) and this resulted in a total of 24 plots of (3 x 2 m) (Figure 10). This grid was then transformed into Photoshop CC 2014 (Figure 10). A grid was laid over quadrat of the autumn photo from each study site, then other repeat photos of following seasons were placed on top of that grid (Figure 10).

Since the grid was laid over quadrat in Photoshop CC 2014 (Figures 9 and 10). All the enumeration, measurements and monitoring were undertaken using this application features such as the number of individuals, species richness, vegetation cover %. As well as, their growth rates (e.g. leaf development, plant height, flowering and seed production). The count tool was used to count all the number of individual plants, tracking and record these ecological changes that appeared on the high-resolution repeat parallel panoramic photography (Hall 2001; Hoffman *et al.* 2010; Powell 2013). The groups of counts tool were useful to create a plant species list of these individuals and for indicating these species based on a reference book (Hall 2001; Hoffman *et al.* 2010; Powell 2013; Evening 2014; 2015). A grid was designed to monitor the changes in vegetation cover % from the sampling quadrat of the RP during the growing season in the present study (Moll *et al.* 1984, Hoffman *et al.* 2010; Powell 2013; Emms 2013). The Ruler tool and height sticks measures were used to estimate the measurements of all individual plants height and growth rates above the ground (e.g. leaf development) that appeared closest to the measuring stick on high definition parallel panoramic imagery (Hall 2001; Evening 2015; 2014).

Using a modern computer programme such as Photoshop CC 2014 was more time-efficient. Each study site took five working hours to undertake these various analyses extracted from the images. These photographs sources provided complete coverage of the entire study sites within a short time interval, which can save time and expense relative to conventional field measurements.

CHAPTER 5: RESULTS

5.1 Plant Species Richness and Number of Individual Plants

The results are presented around each research question set:

1) Do species richness and the number of individual plants increases along an increasing altitude gradient in a post-burn Mountain Fynbos?

There was an increase in the number of species and individual plants along the lower altitudinal gradient from 460 m to 490 m as represented by Site 1 and Site 2 (Table 14). Site 2 at an altitude of 490 m had the greatest number of species with n = 20 and individual plants with n = 210. Site 3 at 493 m and Site 4 565 m had much lower species richness, n = eight and n = 15 species respectively and a number of individual plants with n = 84 and n = 81 respectively. Site 5 had an increase in both species richness and number of individual plants with n = 18 and n = 141 respectively (Table 14). These results confirmed that the lower and higher altitudes had the most plant diversity and the middle latitudes had contained the least plant diversity (Agenbag *et al.* 2008).

Table 14. The total number of species and individual plants recorded from 3 m x 2 m quadrats, along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR). The results are aggregated over the one-year post-fire succession period (autumn, winter, spring, summer 2016 and late summer 2017):

Elevation Station	Altitude (m)	Total Number of Species	Total Number of individual plants
Site 1	460 m	15	189
Site 2	490 m	20	210
Site 3	493 m	8	84
Site 4	565 m	15	81
Site 5	626 m	18	141

5.1.1 Plant Species Richness

Plant species richness is lowest with n = eight species per (2 x 3 m) plot at Site 3 and highest with n = 20 species at Site 2 (Figure 15). The next lowest site in terms of species richness is Site 1 with n = 15 species. From autumn 2016 to January 2017 the number of species at each site remained the same (Table 14; Figure 15). The highest altitude Site 5 had the second-highest number of species. There is no obvious trend in species richness with increasing altitude. However, Site 3 does seem to have much lower species richness than the other sites n = eight species compared to n = 15 to n = 20 at the other sites). This suggests that once species are established after a fire the species persist and therefore, species richness is stable in the early post-fire period.

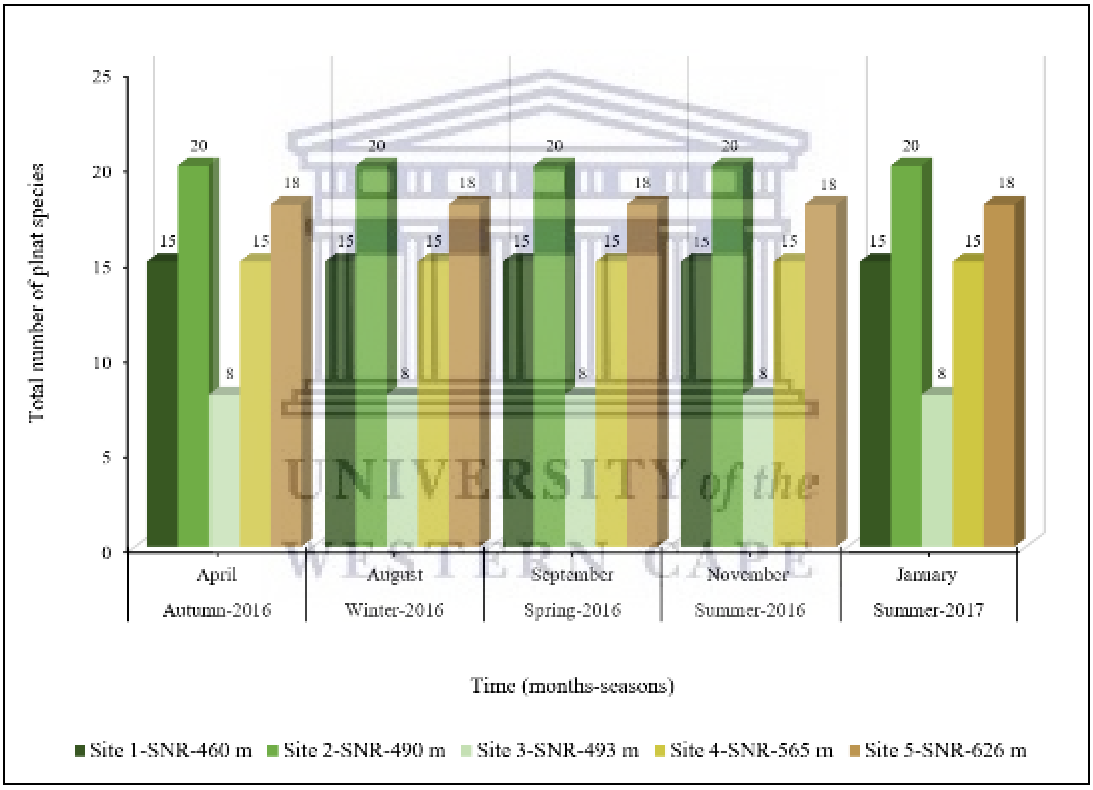

Figure 15. Plant species richness as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from 460 m to 626 m at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

5.1.2 Number of Individual Plants

2) Do the number of species and the number of individual plants shows an increase over the earlier first half of the full season?

There was no overall change in the number of individual plants during the one-year season (Figure 16) and there is a similar trend for the species richness (Figure 15) where there was an identical number of species at each season. Normally one would expect a few recruitments in winter and some mortality during the hot and dry summers. Over the 10-month study period at Site 1, the n = 189 plants dropped to n = 182 in August and then remained the same until the following January (Figure 16). Site 2 had the greatest number of individual plants (Figure 16) as well as the greatest number of species (Figure 15) and only dropped by one individual plant. The period from April to August 2016 seemed to have lost the most number of individual plants (Figure 16).

At Site 1, seven individual plants of *Roella ciliata* appeared to be unhealthy by autumn 2016 and had disappeared by winter 2016 (Figure 17). At Site 2, one individual plant of *Leucadendron laureolum* was dead by autumn 2016 and the dead plant had disappeared by winter 2016 (Figure 18). At Site 3, three individual plants of *Roella ciliata* were missing by winter 2016 (Figure 19), and one individual *Watsonia spp* had dried and had lost its leaves above the ground. Leaves had died back and leave broken down by summer 2016 and had disappeared by summer 2017 (Figure 20).

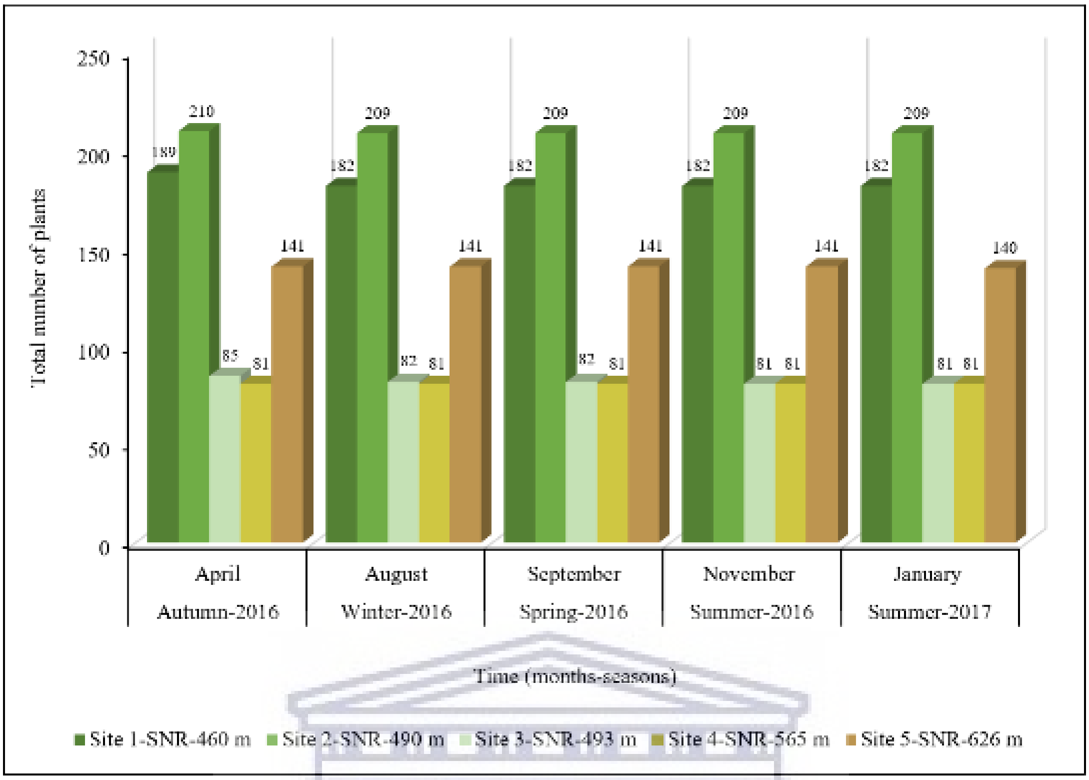

Figure 16. Number of individual plants as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from 460 m to 626 m at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

Figure 17. Tracking the individual plants of herbs as illustrated n = seven *Roella ciliata* plants identified as unhealthy in autumn (April 2016) and had died by winter (August 2016), located at Site 1. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). The imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera-equipped together 45 mm Tilt-Shift lens.

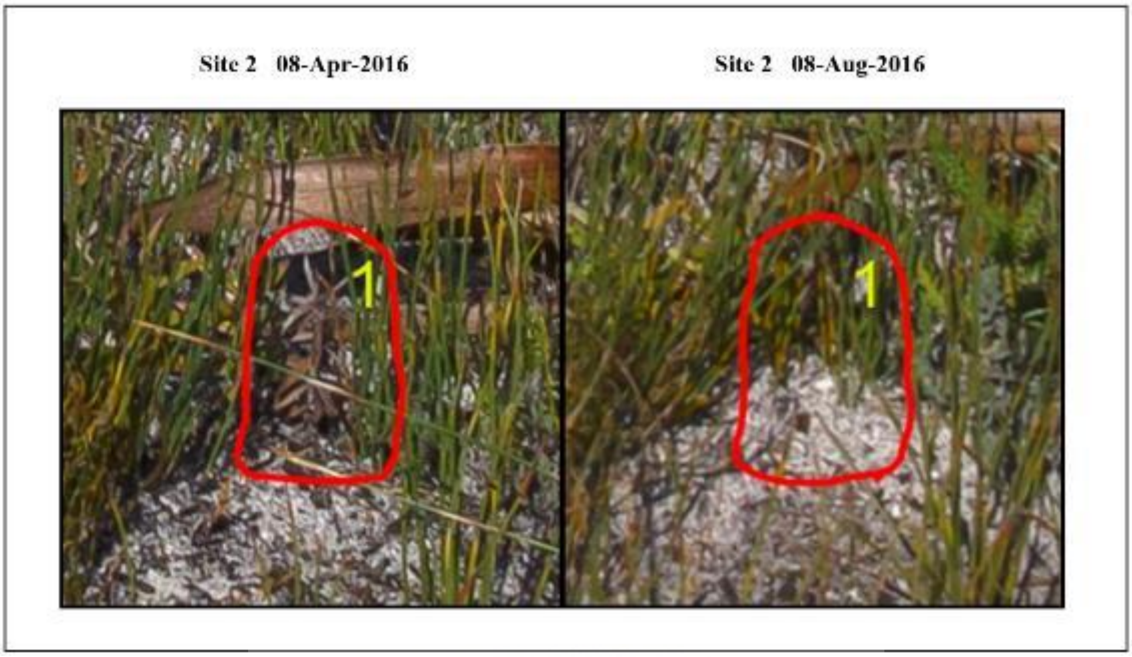

Figure 18. Tracking the individual plant of shrub as illustrated n = one *Leucadendron laureolum* plant identified that had died in autumn (April 2016) then had missed by winter (August 2016), located at Site 2. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

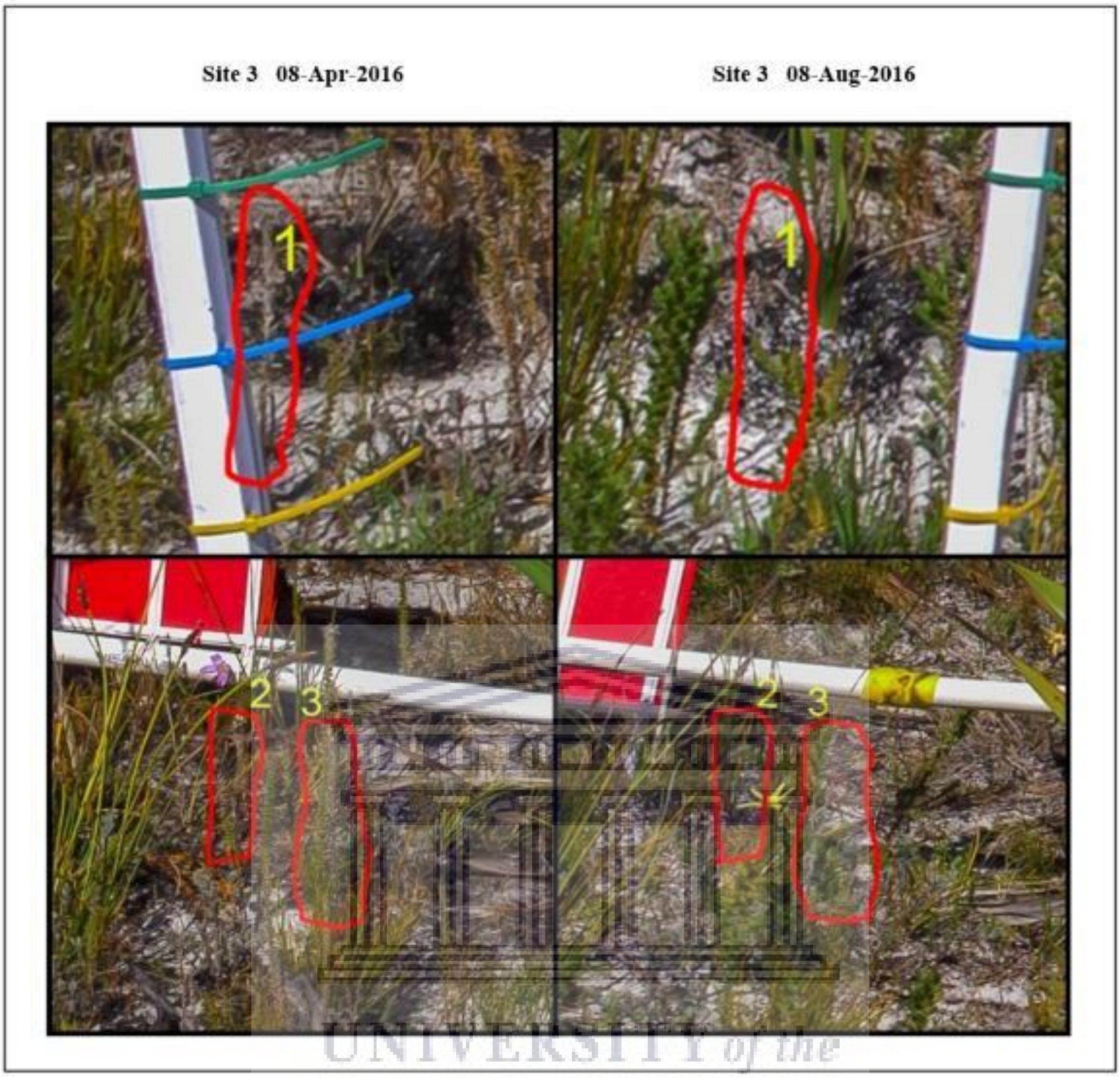

Figure 19. Tracking the individual plant of herb as illustrated n = three *Roella ciliata* plants identified as unhealthy in autumn (April 2016) had died by winter (August 2016), located at Site 3. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

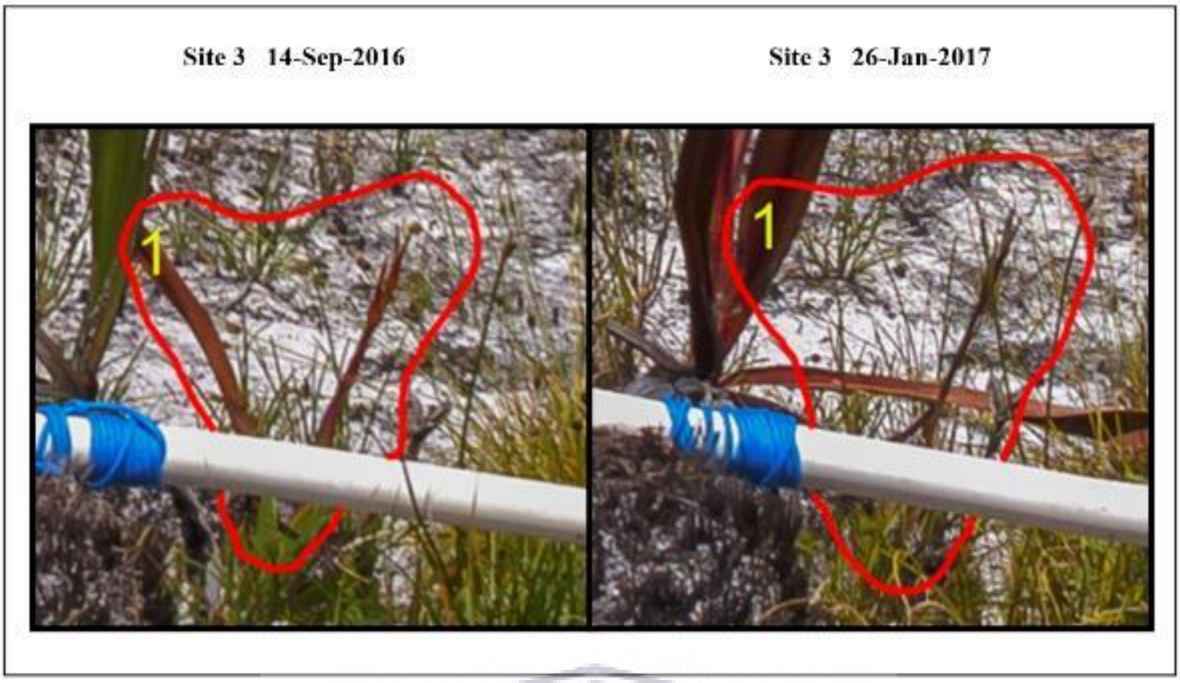

Figure 20. Tracking the individual plant of geophyte as illustrated n = one *Watsonia sp* identified that had dried its leaf and broken all above the ground in early summer (November 2016), then its leaf had missed in late summer (January 2017), located at Site 3. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.2 Growth Forms

3) Since Fynbos is defined as Mediterranean shrubland* do sites dominated by shrubs have a higher species richness than sites with less shrub abundance?

Fixed-point repeat photography (FRP) was able to record and identify the growth forms photographically from 3 x 2 m fixed monitoring quadrats within study sites (Figure 22).

Site 2 had the greatest number of individual shrubs 101 (Figure 21) and was associated with the greatest species richness, n = 20 species (Figure 15) and the greatest number of individual plants n = 210 (Figure 16). Site 5 which is at the highest altitude had the second-highest number of shrubs (Table 14; Figure 21). This supports our hypothesis as expressed above.

Herbaceous plants were highest at Site 1 which was at the lowest altitude and near to the car park and consequently likely to have more disturbance than the other sites.

The low number of geophytes at all sites suggests that they had already completed their cycle following the fire (Figure 21). There were also few succulents (Figure 21), found only at Site 1 (lowest altitude) and Site 5 (highest altitude) (Table 14).

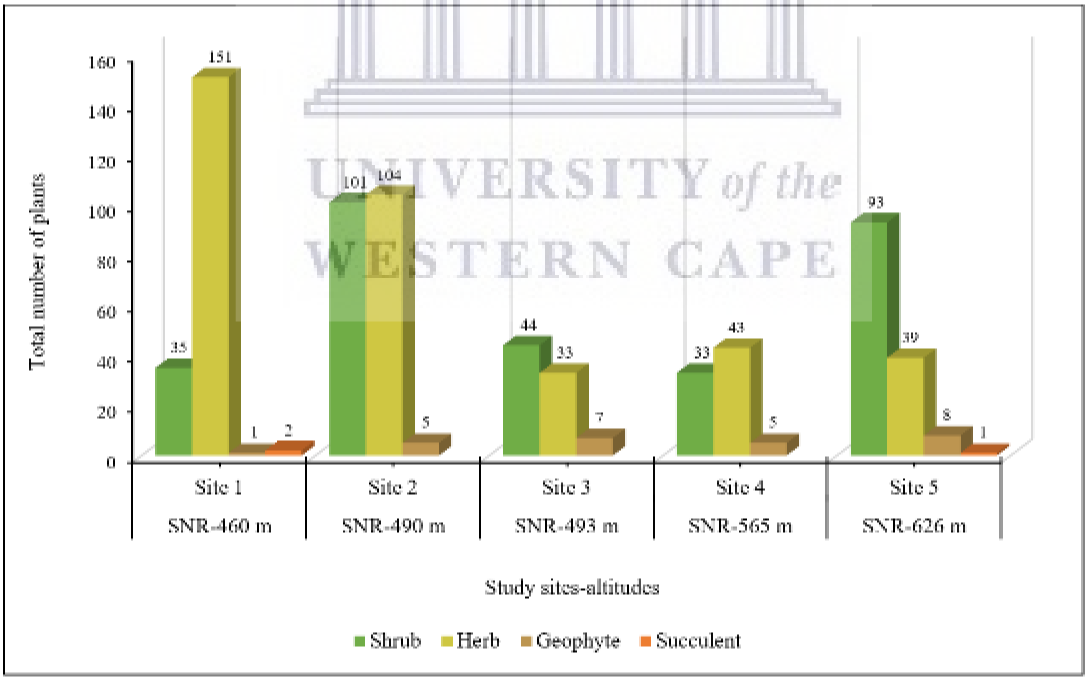

Figure 21. Growth forms as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from 460 m to 626 m at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

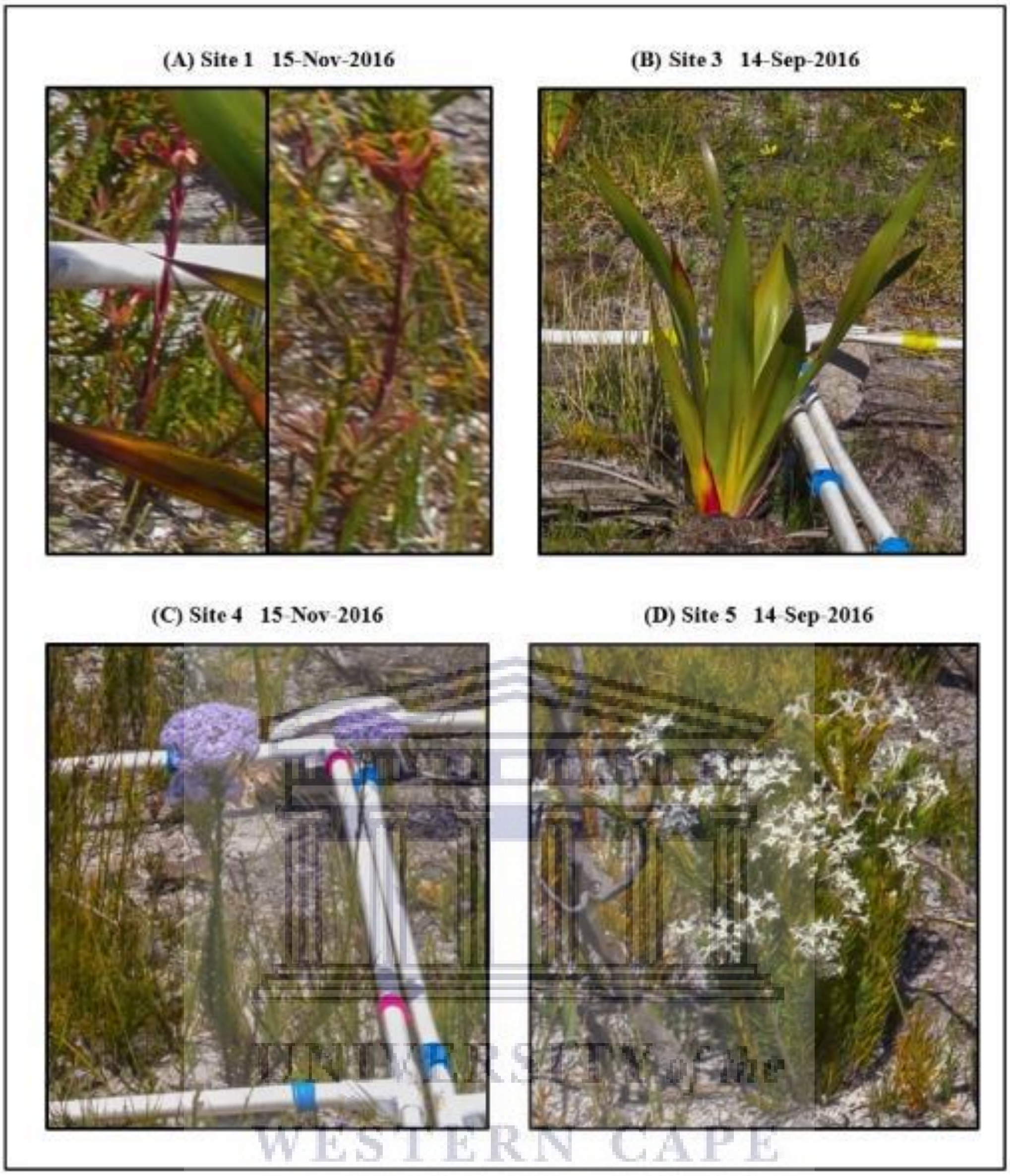

Figure 22. Recording the individual plants of growth forms as illustrated (A) Site 1 succulent, (B) Site 3 geophyte, (C) Site 4 herb and (C) Site 5 shrub. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.3 Total Vegetation Cover (%)

4) Does the vegetation cover change with maturity and is there a clear spring growth peak which is consistent with normal growth patterns in Mediterranean climates?

All five sites showed an increase in the percentage of vegetation cover from autumn 2016 to late summer 2017 (Figure 23). The increase in cover during this period was over 20% at each site. Site 1 has the highest amount of *herbaceous* plants (Figure 21) and had the highest growth cover change which increased from n = 30% to 74% (Figures 23 and 24). At Site 2, the percentage of the total vegetation cover has increased from n = 59% to 87% (Figures 23 and 25), and this site that had the greatest number of species richness (Figure 15), the greatest number of shrubs (Figure 21) and had the greatest increase in plant cover-abundance over the full season (Figures 23 and 25).

In autumn 2016, Site 3 and Site 4 had the lowest percentage vegetation cover of n = 26%, but in late summer 2017, vegetation cover peaked at n = 57% at Site 3 (Figures 23 and 26) and peaked at n = 63% at Site 4 (Figures 23 and 27). Site 3 has the lowest species richness (Figure 15) and has the equal lowest number of individual plants (Figure 16), and the least increase in percentage vegetation cover (Figures 23 and 26).

Site 5 which is the highest altitude (Table 14), had the second-highest number of species richness (Figure 15), had the third-highest number of individual plants (Figure 16) and it had the second-highest number of shrubs (Figure 21). This site had the second-highest increase in plant cover-abundance over the full season (Figures 23 and 28).

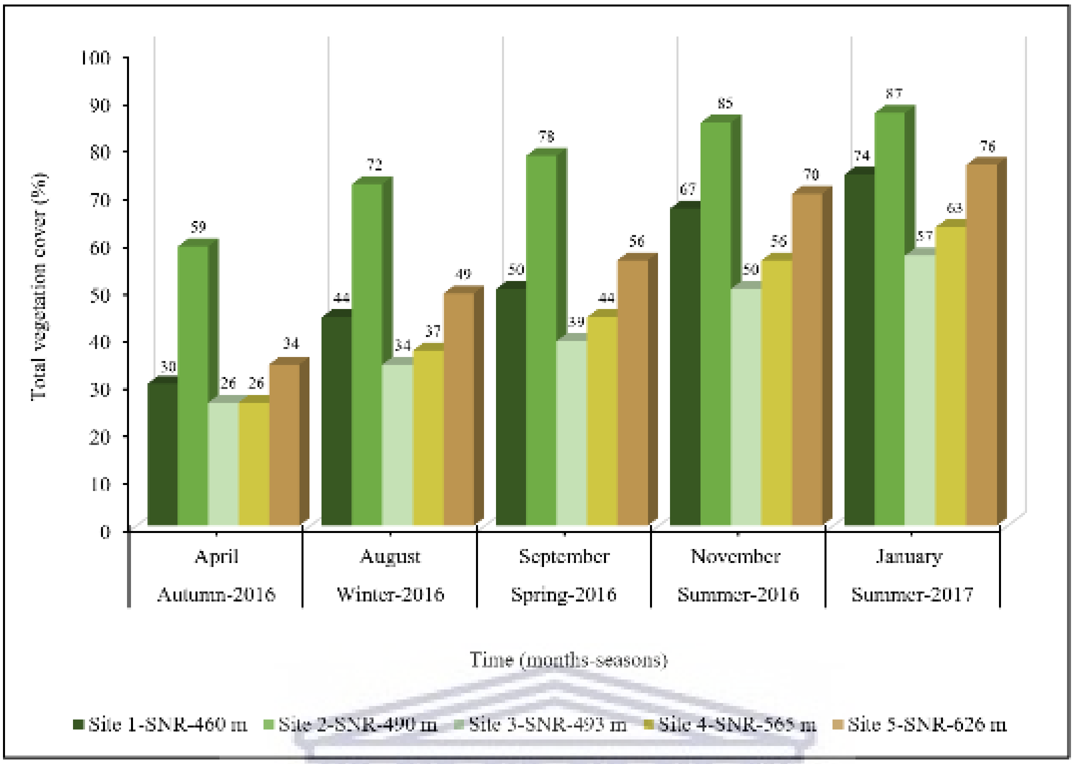

Figure 23. Total vegetation cover (%) as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from 460 m to 626 m at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

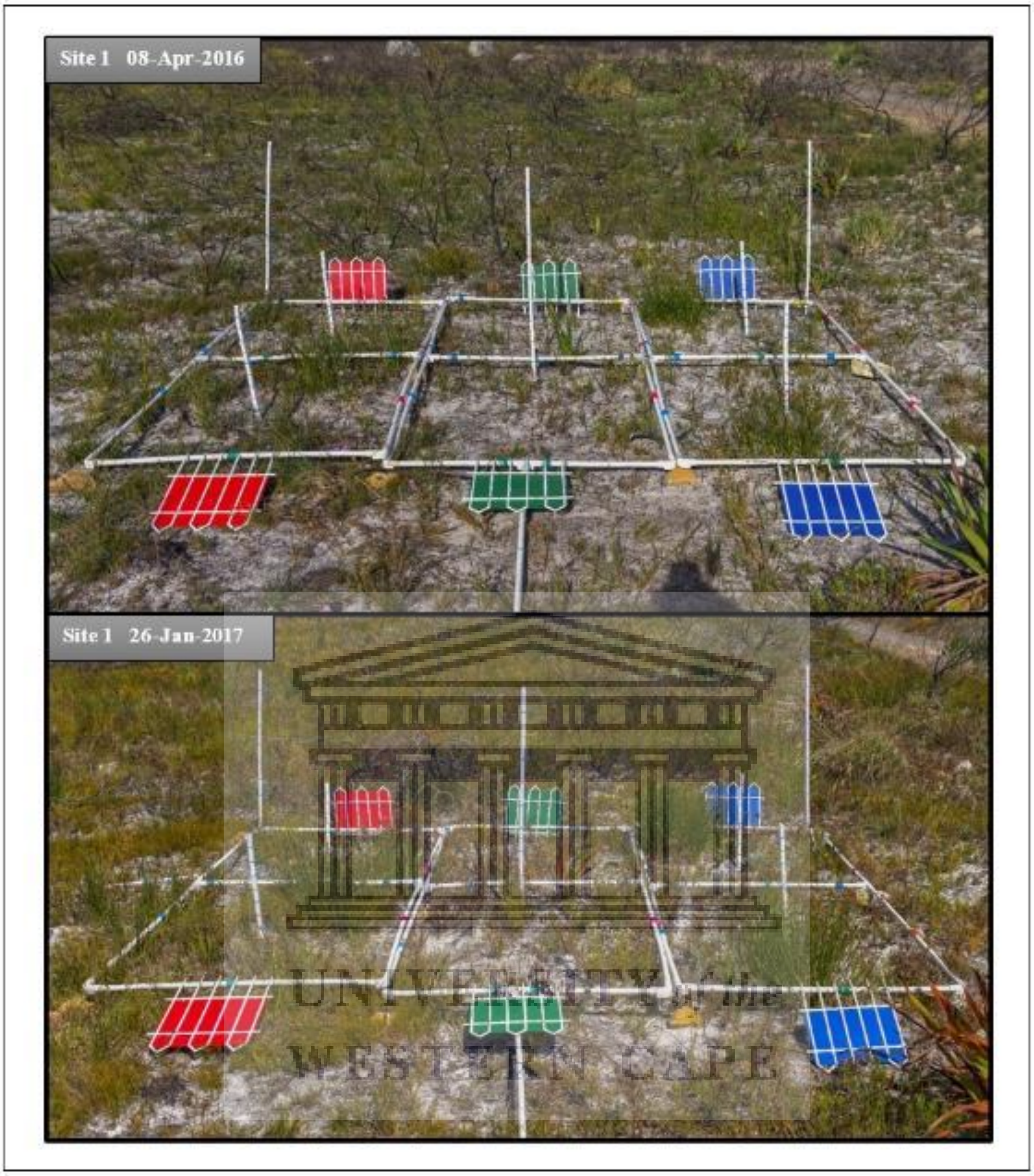

Figure 24. The percentage of the total vegetation cover increased at Site 1 from (30%) in autumn to (74%) in late summer 2017. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

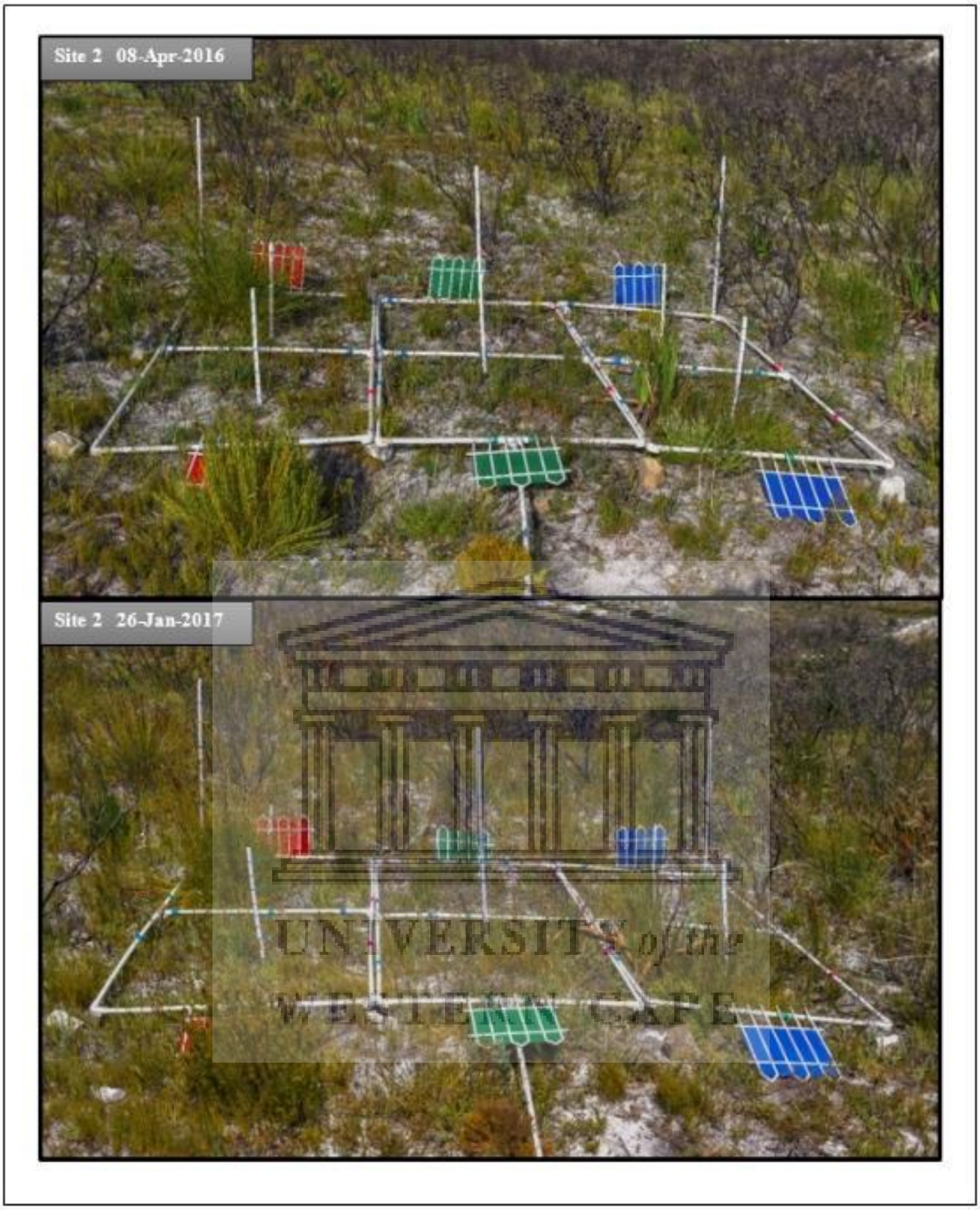

Figure 25. The percentage of the total vegetation cover increased at Site 2 from (59%) in autumn to (87%) in late summer 2017. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

Figure 26. The percentage of the total vegetation cover increased at Site 3 from (26%) in autumn to (57%) in late summer 2017. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

Figure 27. The percentage of the total vegetation cover increased at Site 4 from (26%) in autumn to (63%) in late summer 2017. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

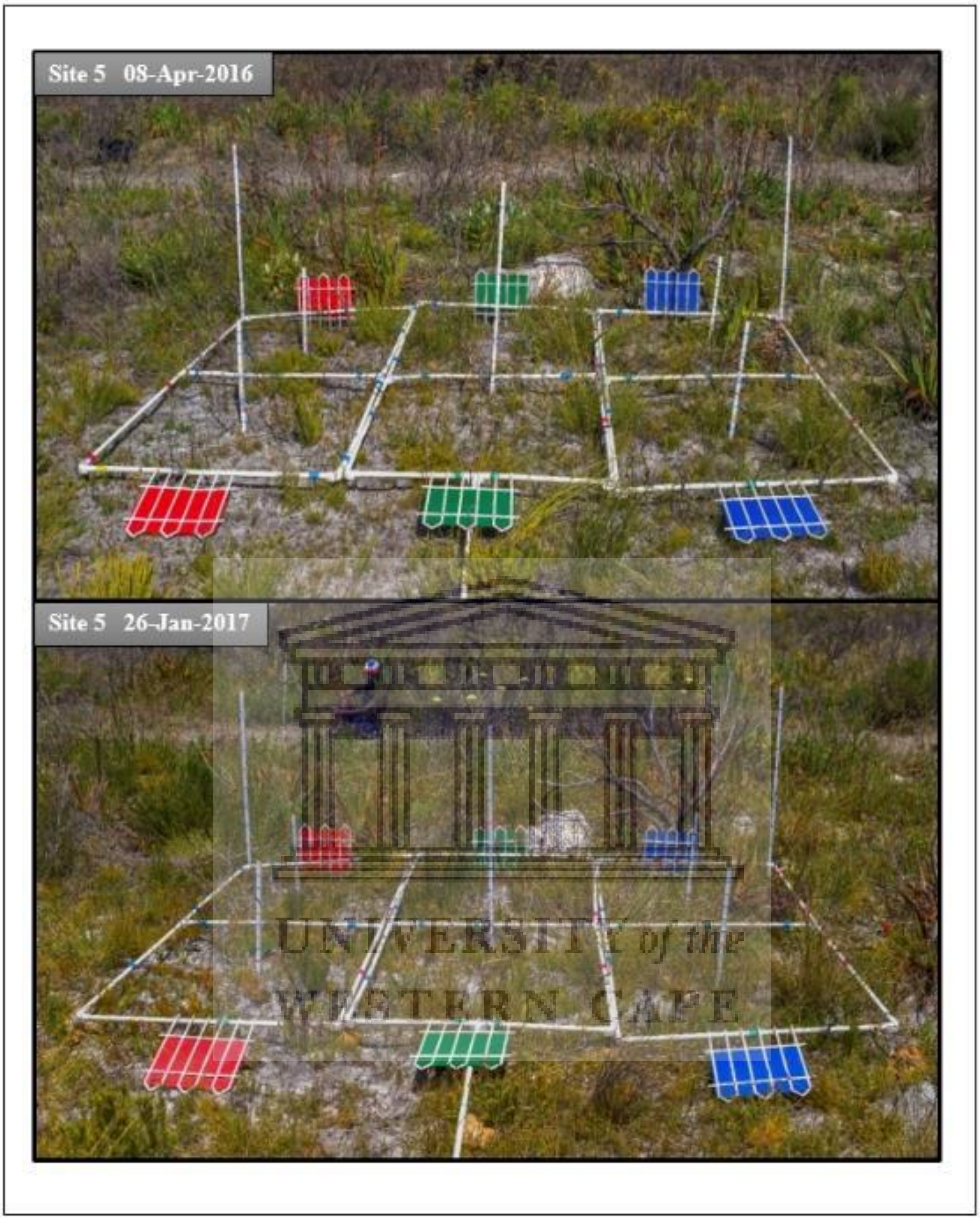

Figure 28. The percentage of the total vegetation cover increased at Site 5 from (34%) in autumn to (76%) in late summer 2017. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.4 Leaf Development

Leaf initiation stage

Autumn 2016 was the only season in which the leaf initiation stage took place, with a total of n = 87 individual plants (Figure 29).

Young leaf stage

From autumn to winter 2016, there were only two periods with a significant amount of number of individual plants with young leaves n=349 in April and 402 in August. There was only n = five individual plants were found to have young leaves in spring 2016 (Figure 29).

Fixed-point repeat photography (FPRP) recorded most of the individual plants had matured their leaves at all study sites from autumn to spring 2016 (Figure 29).

Mature leaf stage

From autumn to spring 2016, there was an increase in the number of individual plants with mature leaves n = 145 in April, n = 416 in winter and n = 686 in September (Figure 29). During summer months, there had been a decrease from n = 660 mature leaves in November 2016 to n = 290 in January 2017 (Figure 29).

Fixed-point repeat photography (FPRP) recorded that the decrease appeared from early summer 2016 to late summer 2017 due to some individual plants with completed growth and their leaves became senescent (Figures 29 and 30 D).

Senescent leaf stage

From autumn to early summer 2016, there had been a small increase in the number of individual plants with senescent leaves n = 13 in April, n = one in August, n = three in September and n = 19 in November (Figure 29). By late summer (January 2017) there was a significant amount of n = 386 individual plants had senescent leaves (Figure 29).

Fixed-point repeat photography (FPRP) recorded that some species were found to have senescent leaves in Autumn (April 2016) and they did not look healthy enough to survive by the following post-fire months (Figures 17; 18 and 19). In winter (August 2016) these individual plants were non-existent (Figures 17; 18 and 19). In spring 2016, there were individual plants that had died back their leaves and became senescent (Figure 29). From early summer to late summer (November 2016 to January 2017) most individual plants had finished their growth, their leaves had died and turned to senescent leaves (Figures 29 and 30 D).

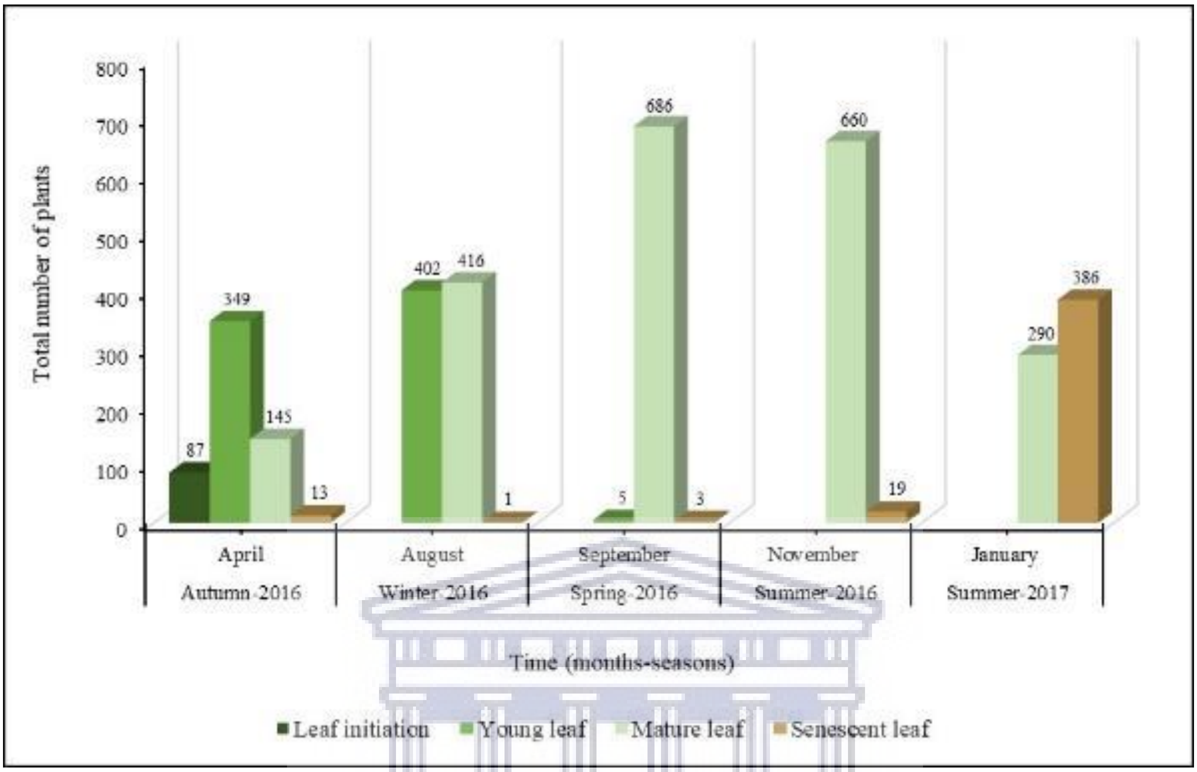

Figure 29. Leaf development on individual plants as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

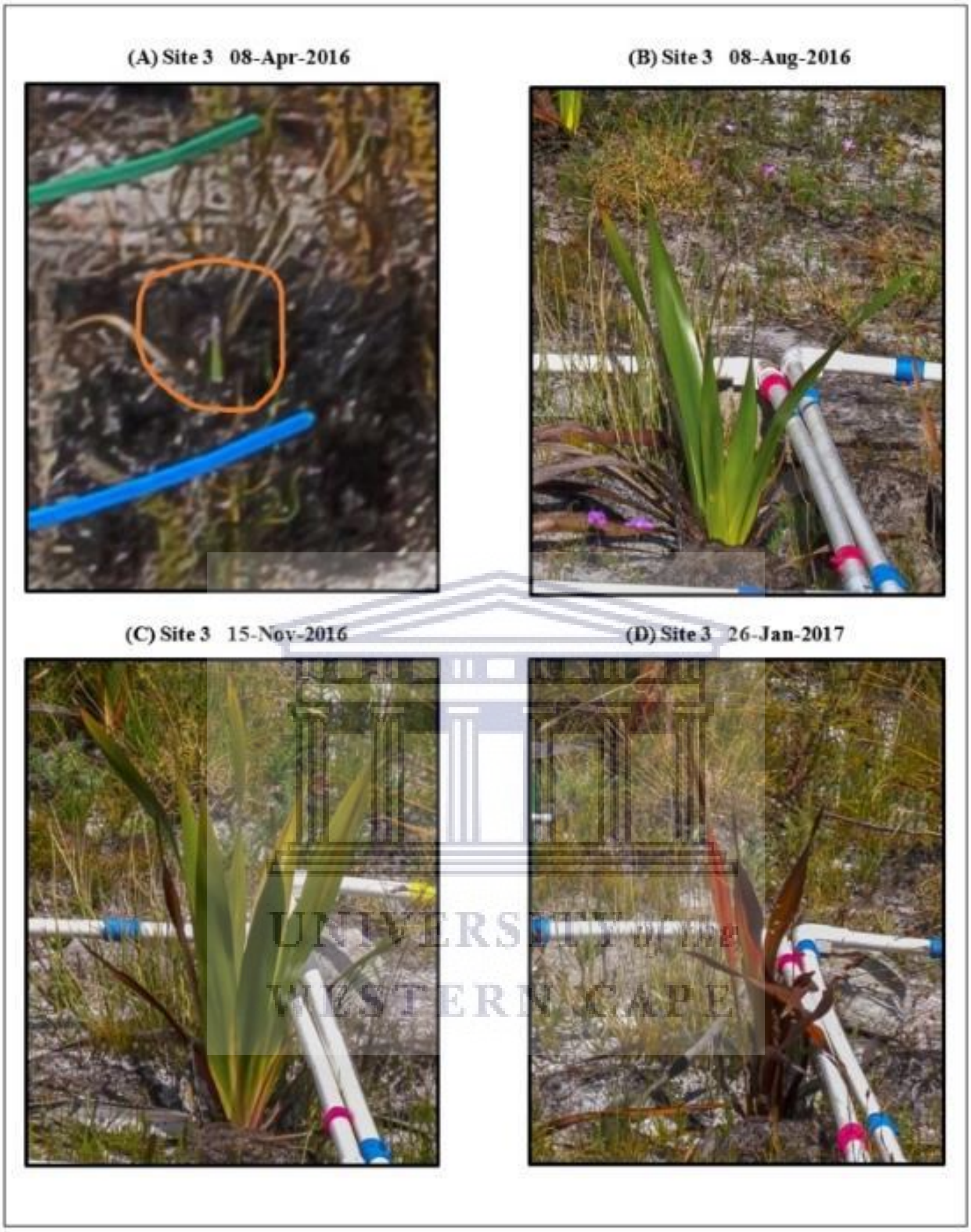

Figure 30. Tracking the leaf development of geophyte of n = one *Watsonia sp.* as illustrated (A) leaf initiation stage in autumn (April 2016), (B) young leaf stage in winter (August 2016), (C) mature leaf stage in early summer (November 2016), (D) senescent leaf stage in late summer (January 2016), located at Site 3. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.5 Predominant Leaf Colour Conditions

Leave status: Mostly green

Autumn (April 2016) had the highest number of individual plants namely n = 568, with predominantly green leaves (Figure 31). The number of individual plants with predominating green leaves remained fairly constant through winter n = 560 into spring n = 536 (Figure 31). However, by early summer (November 2016), the number had dropped to n = 430 individual plants, then in late summer (January 2017) it further decreased to n = 318 individual plants (Figure 31).

Fixed-point repeat photography (FPRP) recorded some individual succulents that were mostly green within the initial growth in autumn (Figure 31). During winter 2016, these individual plants of young green leaves developed to orange and red pigments and n = one succulents to a red pigment (Figure 34). From autumn to spring 2016 some individual shrubs had their leaves matured to a light green colour (Figure 33). Some shrubs also had their leaves matured to orange (Figure 35). Certain herbs showed a change in pigmentation from a green colour to a dark magenta pigment (Figure 36).

During the summer months (November 2016 – January 2017), some shrubs, herbs and geophytes had fished the growth and their leaves pigmented to transitional colours (mixed green and yellow pigments) (Figure 37). Also, some individual plants of these growth forms, dried and turned brown (Figure 32 B). In late summer n = 318 individual plants of these growth forms were still mostly green and had no change in the leaves colour (Figure 34).

Leave status: Pigmented (a mixture of orange, red or dark magenta pigments)

Pigmented leaves are defined as leaves that are red-like in colour. The following species are examples of plants possessing pigmented leaves: *Crassula fascicularis* which have a red pigment (Figure 34). *Thesium acuminatum* which have an orange pigment (Figure 35). *Senecio pubigerus* has a dark magenta pigment in colour (Figure 36).

During autumn 2016 to late summer 2017, the number of individual plants with pigmented leaves increased from n = 49 in April to n = 51 in winter, n = 55 in spring, n = 56 in November 2016 and finally, n = 66 in January 2017. This pattern is likely to be due to the process of maturation of the leaves cells associated with pigmentations (Figure 31).

Leave status: Light green

Light green leaves are defined by species that have a silvery appearance virtually covered by reflective hairs and are represented by species such as *Gnidia anomala and Syncarpha vestita* (Figure 33). These species have typical physiological development of the leaves to reduce the loss of water during the Mediterranean dry summer conditions.

From autumn 2016 to early summer 2016, there had been a piecemeal increase in the number of individual plants with light green leaves April n = 101, August n = 110, September n = 129 and November n = 147 (Figure 31). In late summer 2017, the number of plants with silver-green leaves had dropped to n = 125 individual plants, due to plant mortality (Figure 31).

Fixed-point repeat photography (FPRP) recorded the characteristics of the phenological development of the individual leaves of plants. From autumn 2016 to summer 2016 showed some individual plants of growth form such as shrubs matured their leaves to light green. In late summer 2017, this drop occurred due to some individual plants of shrubs had completed the growth, dried and turned to brown. Also, n = one individual plant of herb developed its leaf colour from the light green to a green colour (Figure 31).

Leave status: Transitional leaf colours (mixed green and yellow pigments)

Transitional leaf colours are caused by a decline in chlorophyll in the plant leaves that represented with mixed green and yellow pigments (complete the growth and before the turn to brown colour) such as *Pseudoselago spuria* and *Arctotis acaulis* as shown in (Figure 37).

From autumn to spring 2016, there had been a too small gradual increase of the number of individual plants with transitional leaf colours - April n = one, August n = two and spring n = three (Figure 31). During summer months, there had been increased sharply to n = 86 in November 2016 and n = 346 individual plants in January 2017 (Figure 31).

During summer months (November 2016 – January 2017), FPRP recorded most individual plants of shrubs, herbs and geophytes had completed their growth and their leaves pigmented to the mixed green and yellow pigments (Figures 31 and 37).

Leave status: Mostly brown leaves

The mostly brown leaves represented plants that completed their growth, their leaves had dry, died back and turned to brown such as *Watsonia spp* (Figure 32 B).

In autumn 2016, there were n = 12 individual plants with fully brown leaves. There had been a small increase from spring n = one to early summer 2016 n = four. Followed by a significant increase in late summer 2017 (65) (Figure 31).

Fixed-point repeat photography (FPRP) recorded some individual plants of growth forms such as shrubs and herbs that were not healthy in autumn 2016, classified to brown leaf and were missed in winter 2016 (Figures 17; 18; 19 and 31). During the summer drought (November 2016 – January 2017), some individual shrubs, herbs and geophytes finished their growth, their leaves had died back and turned to brown (Figures 31 and 32 B).

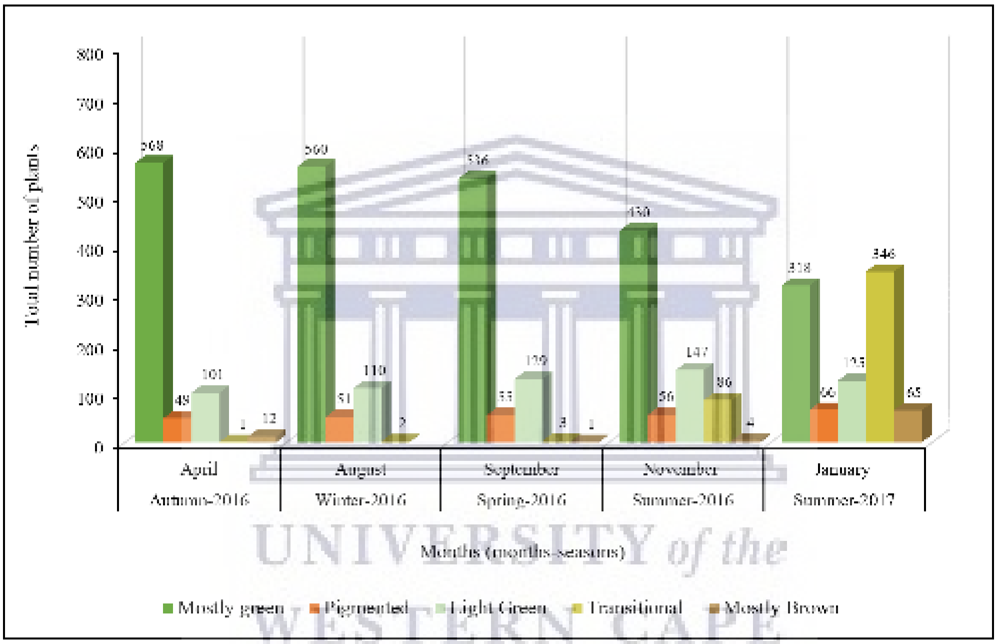

Figure 31. The phenological development of the predominant leaf colours conditions, as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

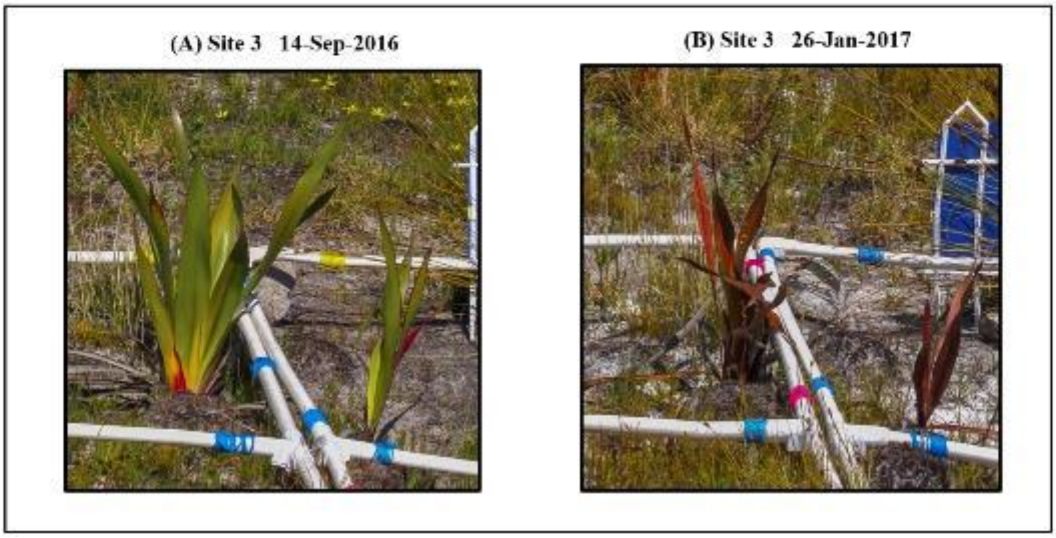

Figure 32. Tracking the leaf colouration of geophytes changed from (A) mostly green to (B) mostly brown as illustrated *Watsonia sp.*, located at Site 3. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

Figure 33. Record the predominant leaf colours conditions (light green) of shrubs as illustrated (A) Site 2 *Gnidia anomala* (B) Site 3 *Syncarpha vestita*, located at Silvermine Nature Reserve (SNR). Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

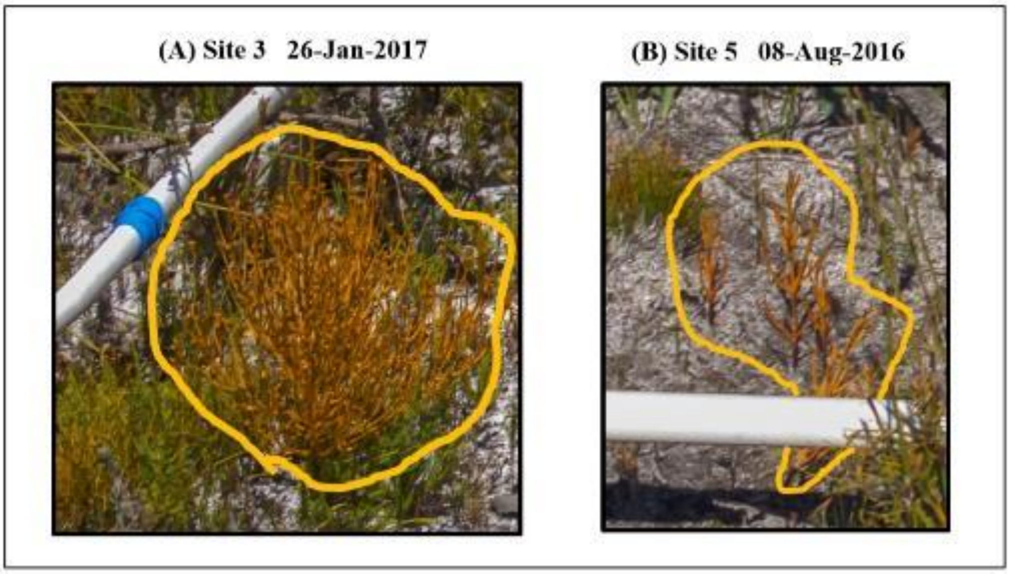

Figure 34. Record the predominant leaf colours conditions (orange pigment) of shrubs as illustrated *Thesium acuminatum* located at Site 3 and Site 5. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

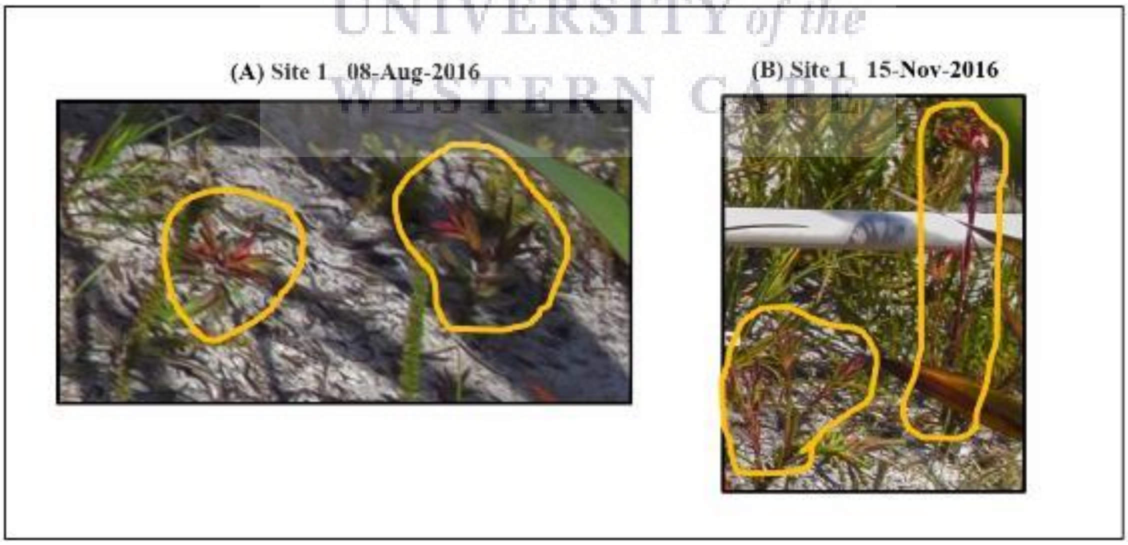

Figure 35. Record the predominant leaf colours conditions (red pigment) of succulents as illustrated *Crassula fascicularis*, located at Site 1. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

Figure 36. Record the leaf colouration of herb pigmented from green to the dark magenta pigment as illustrated *Senecio pubigerus,* located Site 3. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

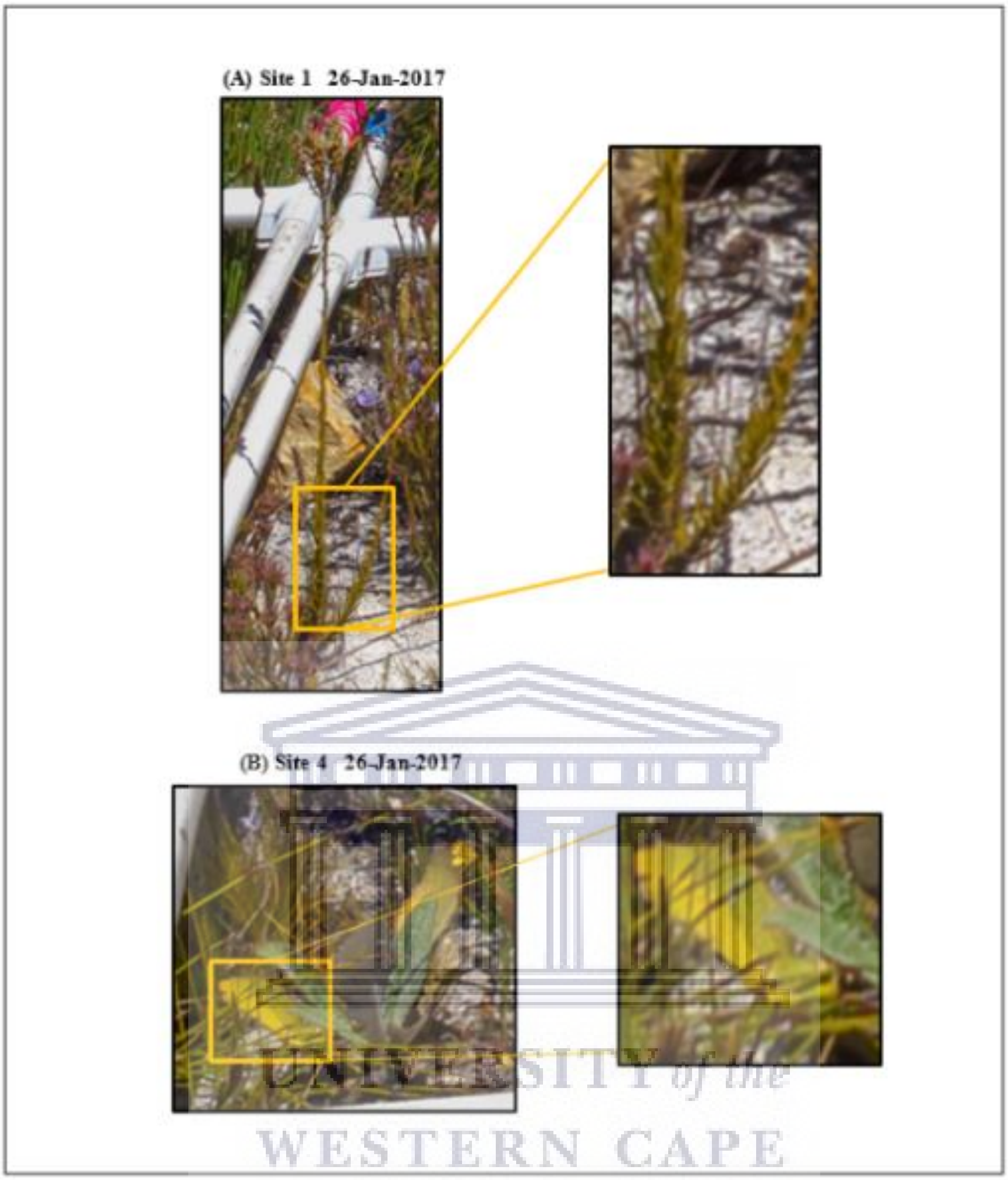

Figure 37. Record the leaf colouration of herbs pigmented from green to the transitional colour (mixed green and yellow pigments) as illustrated (A) Site 1 *Pseudoselago spuria* and (B) Site 4 *Arctotis acaulis*. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.6 Flowering Phenology

Non-flower stage (Plants without flowers)

The non-flower stage is defined by species that had no flowers or without flowers (had not flowered yet) such within the initial growth stage as *Pseudoselago spuria* (Figure 40 A), or these individual plants had lost their old sepals (calyx) and became non-flowering.

From autumn to winter 2016, there had been an increase in the number of individual plants without flowers n = 574 in April 2016 and n = 597 in August 2016 (Figure 38). From spring to early summer 2016, then there had been a slight gradual decrease n = 535 in September 2016 and n = 523 individual plants in November 2016 (Figure 38). There was a significant increase in late summer 757 (Figure 38).

The results from (Figure 38) showed that a significant increase in the number of individual plants without flowers occurred in autumn 2016 and late summer 2017 (Figure 38). Fixed-point repeat photography (FPRP) recorded the majority of plants to have not flowered from autumn 2016 to late summer 2017, due to many of the reported plants being shrubs and were not yet sufficiently mature; this was more than 14-23 months after the fire of February 2015 (Figure 38).

Flower bud stage

Flower buds that represent the plants start to produce the flower buds or flowers at a certain time of the year such as *Pseudoselago spuria* (Figure 40 B).

From autumn to spring 2016, there had been a gradual increase in the number of individual plants with flower buds' n = 19 in April, n = 41 in August and n = 113 in September 2016 (Figure 38). Through summer months, there had been a significant drop in individual plants n = 20 in November 2016 and n = 14 in January 2017 (Figure 38).

Fixed-point repeat photography (FPRP) tracked the development of the flower buds of growth forms such as shrubs, herbs, geophytes, succulents from autumn through to spring 2016, by which time they had matured full blossoms more than 14-19 months after the fire of February 2015 (Figure 38).

Flower initiation (flower buds) peaked in spring, continued and completed by summer months 2016 - 2017 (Figure 38). During the summer months (November 2016 – January 2017), the flower buds declined off in some individual plants of growth forms e.g. shrubs and herbs had developed into full flowering after more than 21-23 months after the fire of February 2015 (Figure 38). There would be a few new flower bud until the following autumn.

Flowering stage (Blooming)

Flowering plants are recorded as these individual plants that bloomed during the year of post-fire months and included species as *Pseudoselago spuria* (Figure 40 C).

From autumn to winter 2016, there were very few individual plants that had bloomed - n = 9 in April, which had dropped to n = 3 in August 2016 (Figure 38). In spring 2016, pack flowering was n = 28 individual plants and continued at the high number, which builds up from spring until early summer 2016 n = 96 individual plants (Figure 38). During the late summer of 2017, the number of flowers showed a further decline n = 81 individual plants in January 2017 (Figure 38).

In autumn 2016, FPRP monitored some individual plants of *Senecio purpureus* were bloomed but its leave had not grown yet (Figure 41 A). Besides, n = one individual plant of *Roella ciliata* were bloomed but when it was in the first growth phase in autumn 2016, after more than 14 months after the fire of February 2015 (Figure 41 B). The flowering peak n = 80 % of all flowers occurred during the summer months (November 2016 and January 2017), and some individual plants of growth forms such as shrubs, herbs, succulents completed the blooming stages and became senescent flowers, after more than 21-23 months after the fire of February 2015 (Figure 38).

Senescent flowers stage

Senescent flowers are defined as flowers that have completed their blooming stages. These represented by species such as *Pseudoselago spuria* (Figure 39 A), *Roella ciliate* (Figure 39 B), and *Watsonia sp.* (Figure 39 C).

From autumn to spring 2016, there had been a gradual decrease in the number of individual plants with senescent flowers n = 102 in April 2016, n = 56 in August 2016 and n = 18 in September (Figure 38). During summer months 2016 - 2017, the number of individual plants had increased from n = 55 in November 2016 to n = 343 in January 2017 (Figure 38).

In autumn 2016, FPRP identified some of these individual plants of *Roella ciliata* were retaining the old sepals (calyx) (Figure 39 B). Also, some individual plants of *Watsonia spp.* were still keeping the old flower pipes after more than 14 months after the fire of February

2015 (Figure 39 C). Most senescent flowers were recorded in the summer months (November 2016 and January 2017) accounting for almost n = 60% of all flowers. This suggests that most plants species flowered and finished flowering in the early summer months (Figure 38).

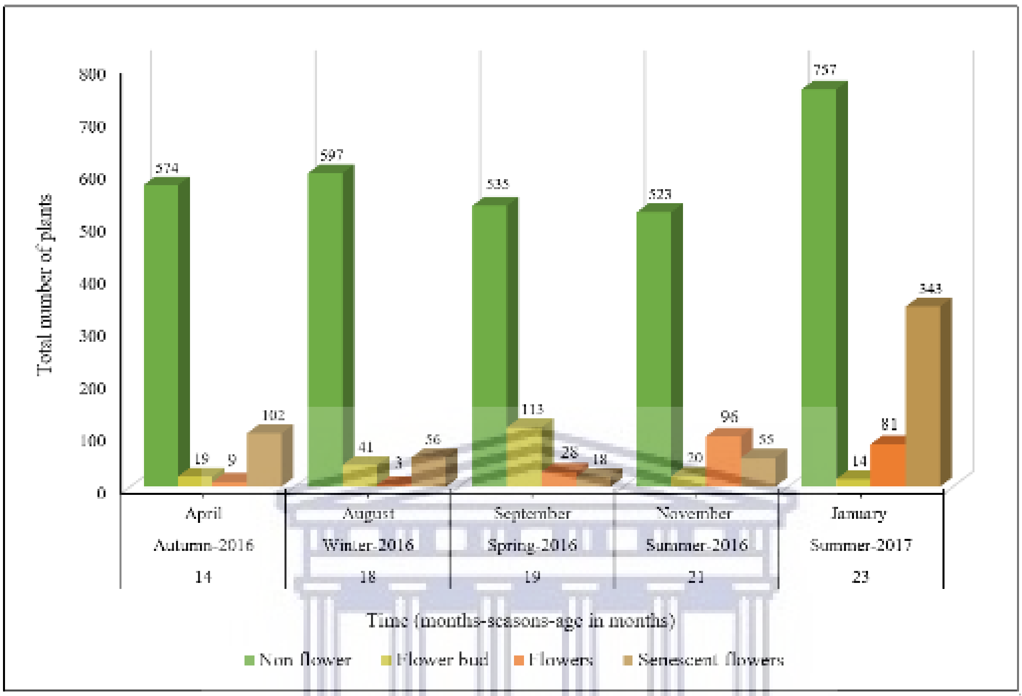

Figure 38. Stages of flowering phenology as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

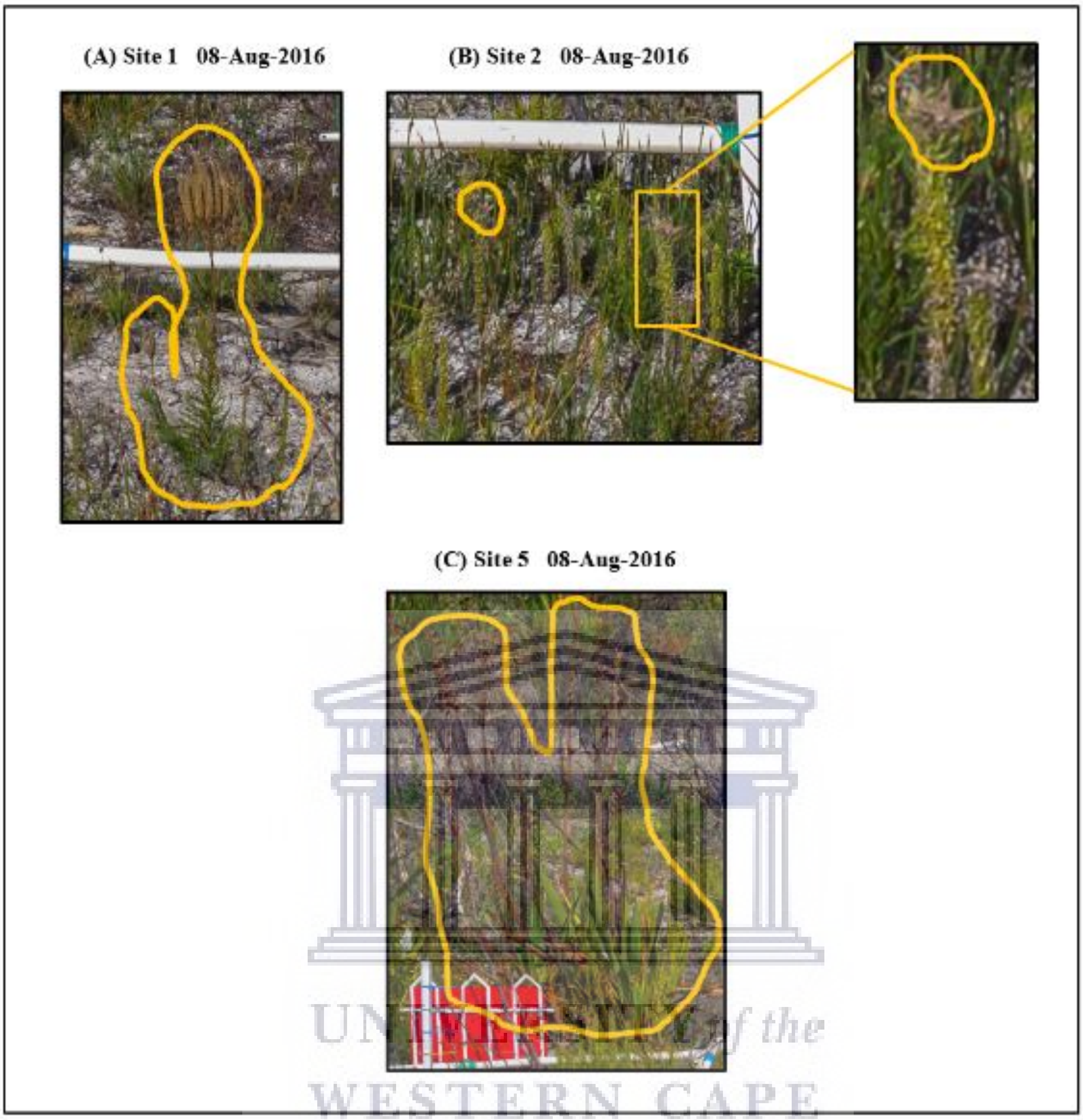

Figure 39. Record the growth forms with senescent flowers in autumn 2016 as illustrated by (A) Site 1 herb, *Pseudoselago spuria* was still retaining the old sepals (calyx) after their flowers lost their petals from the last bloom but in the first growth phase. (B) Site 2 herbs, *Roella ciliata* were still retaining the old sepals (calyx) after their flowers lost their petals from the last blooming, but when it was a small seedling. (C) Site 5 geophytes, *Watsonia sp.* were still retaining the old flower pipes, after their flowers lost their petals from the last bloom. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

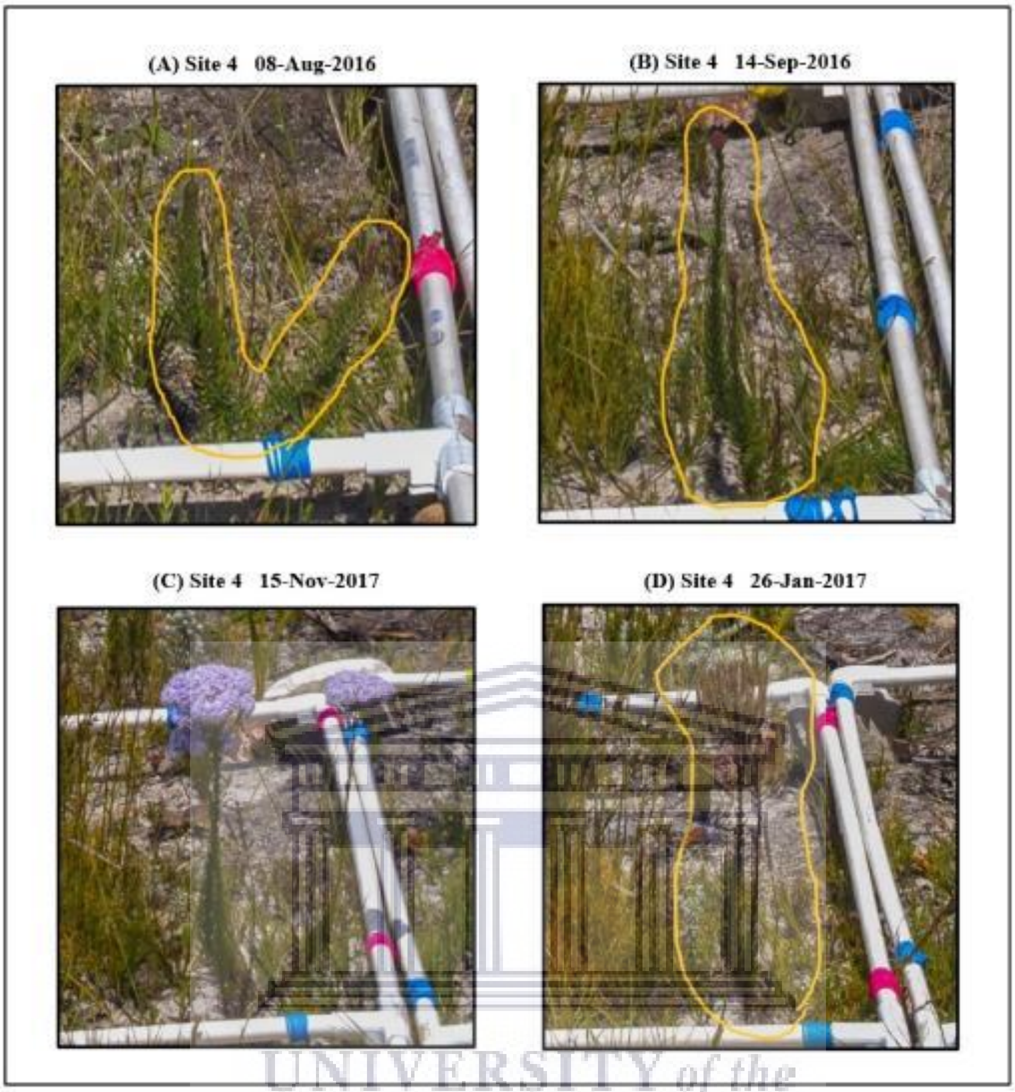

Figure 40. Tracking the flowering phenology stages of herb as illustrated *Pseudoselago spuria* (A) Non-flower, figure (B) flower bud stage, (C) flowering stage and (D) senescent flower stage, located at Site 4. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

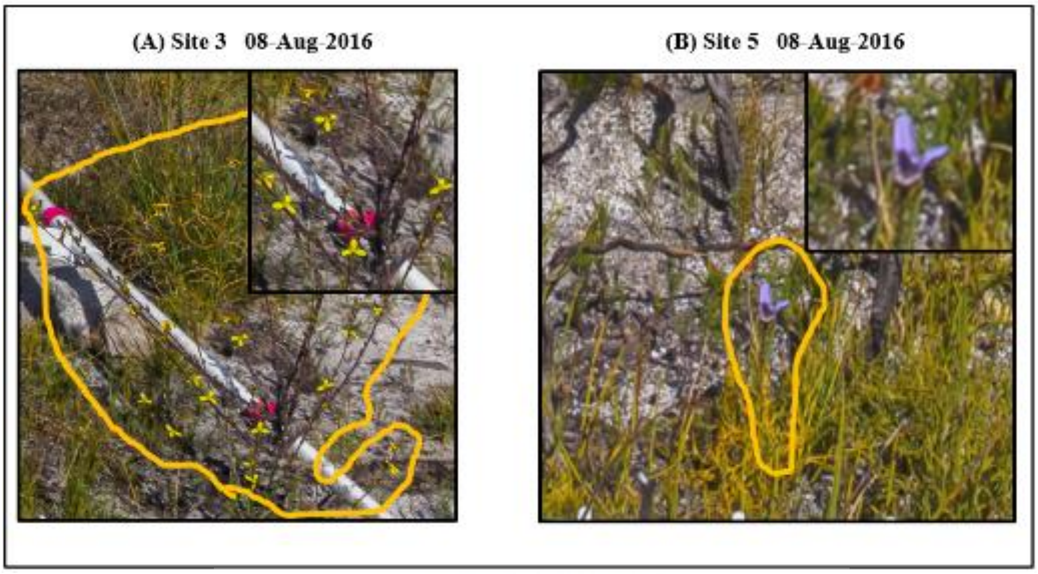

Figure 41. Recording the flowering phenology of n = two individual plants of herbs were flowering early in winter 2016 as illustrated by (A) Site 3 *Senecio purpureus* were flowering but without leaves and (B) Site 5 *Roella ciliata* were bloomed but when it was a small seedling. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.7 Plant Height

Cohort 1 (<50 mm) plants height

From autumn 2016, the number of plants in this cohort decreased through winter n = 144, spring n = 79 and early summer 2016 n = 54 (Figure 42). This very likely reflected the number of plants moving from one cohort into the next highest cohort (Figure 42). However, in January there was a second smaller pack of this cohort (99) (Figure 42).

In autumn 2016, FPRP recorded that most of the individual plants of shrubs, succulents, geophytes, and herbs were small plants at a height ≤ 50 mm (Figure 43 A). During the summer months 2016-2017, some individual herbs completed growth stages and become senescent, so the leaves dried and the plants lost some of their parts and then reduced in size to ≤ 50 mm in height (Figure 20).

Cohort 2 (50-250 mm) plants height

As expected the second period of sampling (August 2016) reported the highest number of the second height cohort (491) (Figure 42). This cohort remained the largest cohort throughout the study period (Figure 42). This suggests that many plants moved from the smallest height cohort into this cohort (Figure 42).

There had been a gradual decrease of this height cohort from spring n = 469 through early summer 2016 n = 450. A small increase in late summer 2017 n = 455 of this cohort was observed (Figure 42).

Cohort 3 (250-500 mm) plants height

In this cohort, there was a big change from the second cohort. The number of plants in cohort 3 increased during August 2016 n = 47 in spring n = 132, in early summer n = 177 and late summer n = 178 (Figure 42).

The main result is emphasizing the increase from September in cohort 3. This further increased in November n = 177 at which point the number stayed the same n = 178 in January (Figure 42).

The Fixed-point repeat photography (FPRP) has already been explained as the methodology recorded that some individual plants of geophytes and herpes increased in the length from 250-500 mm to 500-1000 mm during winter 2016. From winter to spring 2016, some plants of shrubs, succulents and geophytes increased their length from 50-250 to 250-500 mm (Figures

42 and 43). Also, some individual plants of geophytes had lost the old flower pipes and decline in the height from 500-1000 mm to 250-500 mm (Figure 42). During the summer drought 2016-2017, some geophytes had finished their growth, the leaves had died back and shorting their height from 500-1000 mm to 250-500 mm (Figures 20; 30 D; 32 B).

Cohort 4 (500-1000 mm) plants height

Plants in this cohort represented the third-largest height cohort. There was a small increase signed n = six in autumn. Then, there had been a small steady increase observed n = 11 from winter 2016 to spring 2016. After there had been a small decrease n = nine remained from early summer 2016 to late summer 2017 (Figure 42).

Fixed-point repeat photography (FPRP) recorded that in winter 2016, some individual plants of growth forms such as geophytes and herbs increased their height from 250-500 mm to 500-1000 mm (Figure 41). During summer months 2016-2017, some plants of geophytes had finished their growth and the leaves had died back shorting their height from 500-1000 to mm 250-500 mm (Figures 20; 30 D; 32 B and 42).

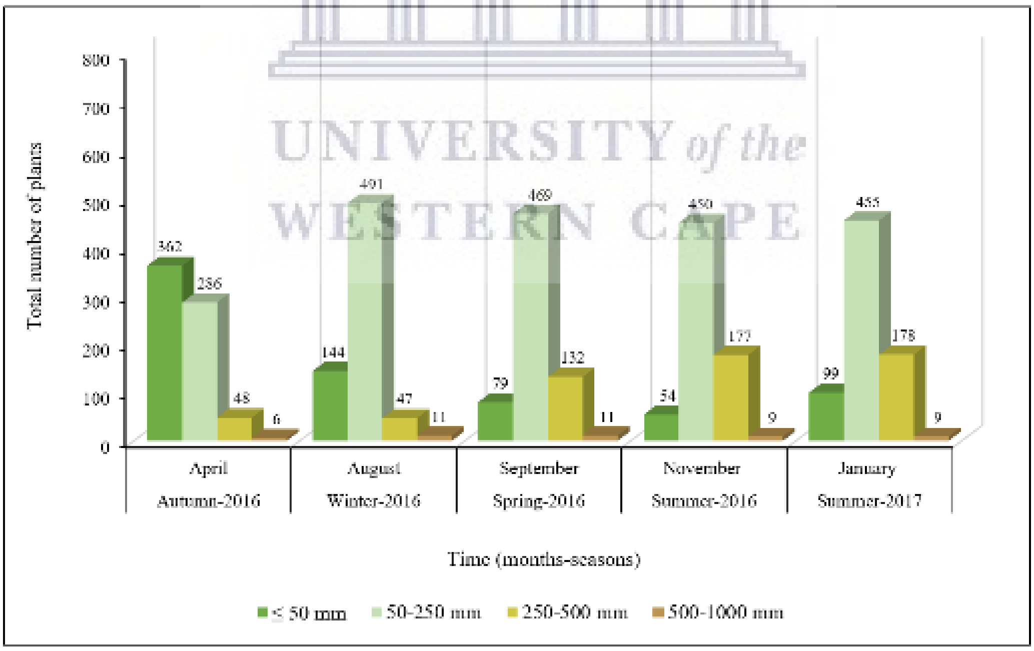

Figure 42. Plant height of individual plants of life forms were measured by using seven measurement height sticks (three with 1000 mm height and four with 500 mm in height) to measure the plants height the above-ground, as recorded photographically from 3 x 2 m fixed monitoring quadrats, at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017).

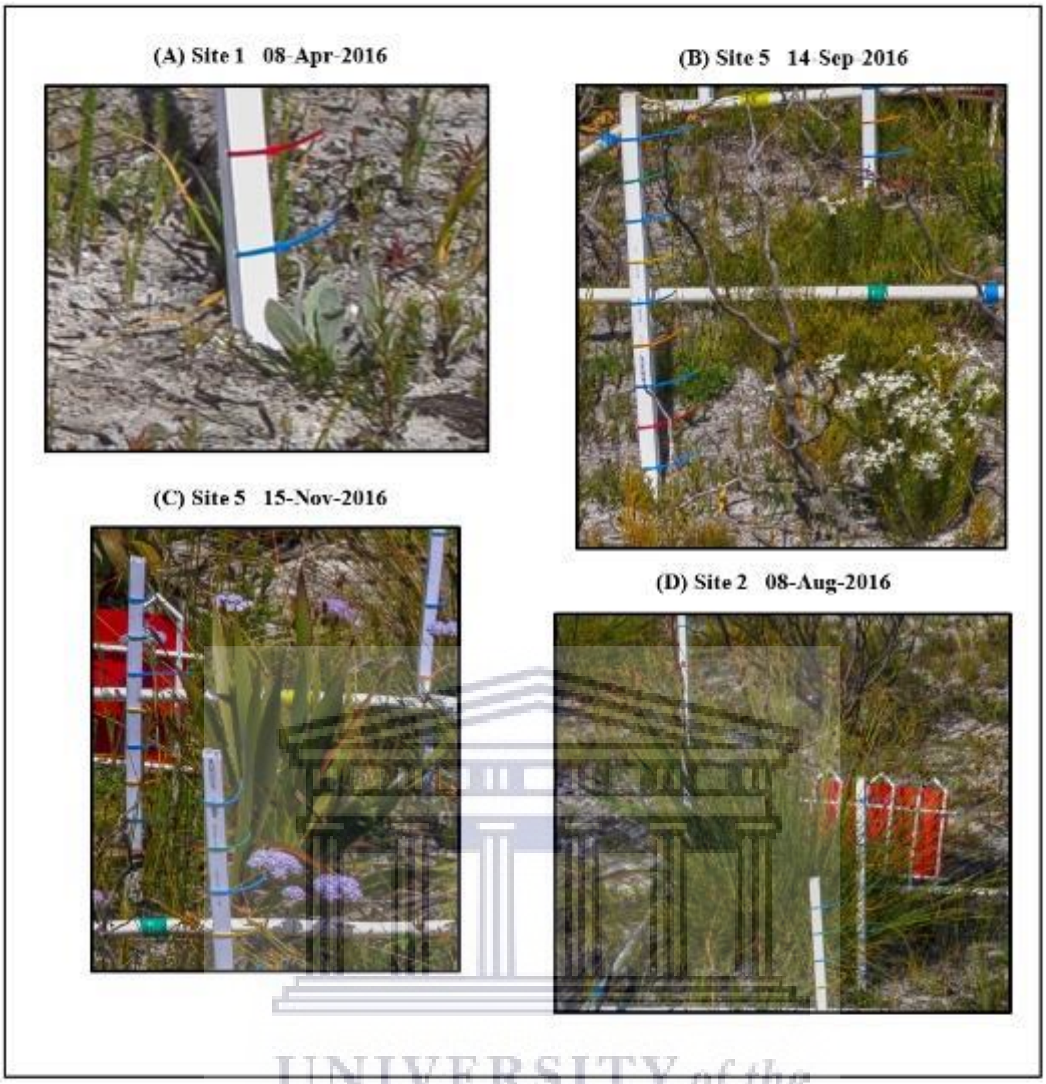

Figure 43. The categories of plant height of growth forms as illustrated by (A) Site 1 (≤ 50 mm), (B) Site 5 (50-250 mm), (C) Site 5 (250-500 mm) and (D) Site 2 (500-1000 mm). Plant height was measured by using seven measurement height sticks (three with 1000 mm height and four with 500 mm in height) to measure the height of the individual plants above-ground. Photos were recorded from fixed monitoring quadrats (3 x 2 m), at five sites arranged along an altitudinal gradient from (460 m to 626 m) at Silvermine Nature Reserve (SNR), during a one-year post-fire succession (autumn, winter, spring, summer 2016 and late summer 2017). Imagery was obtained using three portrait mode images stitched form (11092 x 8565 pixels). The image was acquired using the 51-megapixel Canon 5DS R camera equipped together 45 mm Tilt-Shift lens.

5.8 Regression between Plant Species Richness, Number of Individual Plants and Total Vegetation Cover (%)

5) Can datasets of FPRP explain what is the rate of similarity between plant species richness, number of individual plants and total vegetation cover (%)?

Consequently, my FPRP showed the accuracy of data collection and confirmed the rate of similarity in the relationship between plant species richness, number of individual plants and total vegetation cover within the post-fire of the Mountain Fynbos succession (Figures 44; 45 and 46).

There is no statistical relationship between the total number of plants species and the total number of individual plants (Figure 44). Consequently, all study sites that had more individual plants did not have a statistically significant increase in plant richness. Thus having more individual plants does not lead to a correspondingly increase in the species richness (Figure 44). There is a significant relationship, however, between plant species richness and the total percentage of vegetation cover (Figure 45). There is also a strong relationship between the total number of individual plants and the total percentage of vegetation cover, which is to be expected (Figure 46).

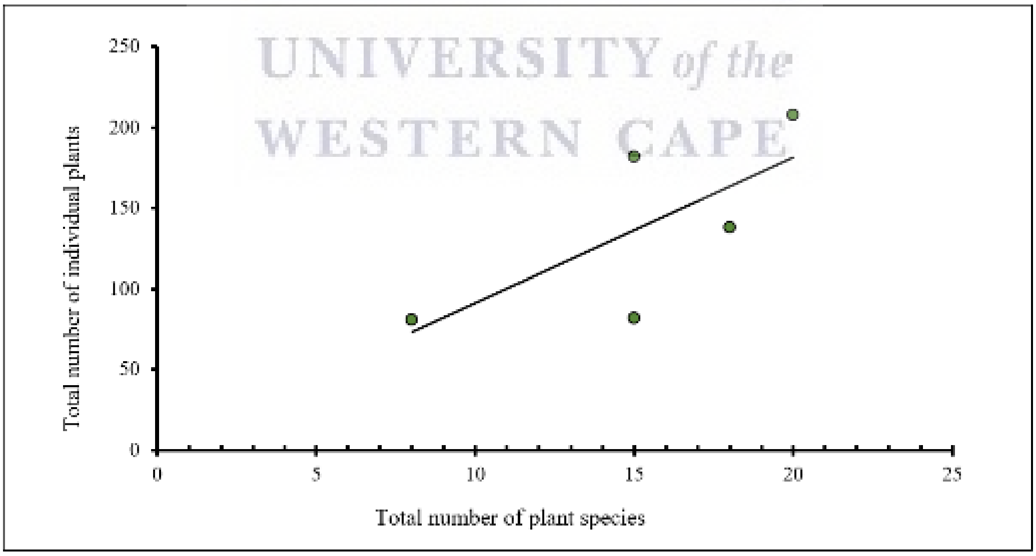

Figure 44. Linear regression for the relationship between total number of plant species and the total number of individual plants: (Y= 9.0435x + 0.7391, R^2 = 0.5122). This graph shows the lack of the statistically significant relationship between the total number of plant species and the total number of individual plants from an analysis of repeat photography during post-fire months after April 2016 to January 2017 at Silvermine Nature Reserve (SNR).

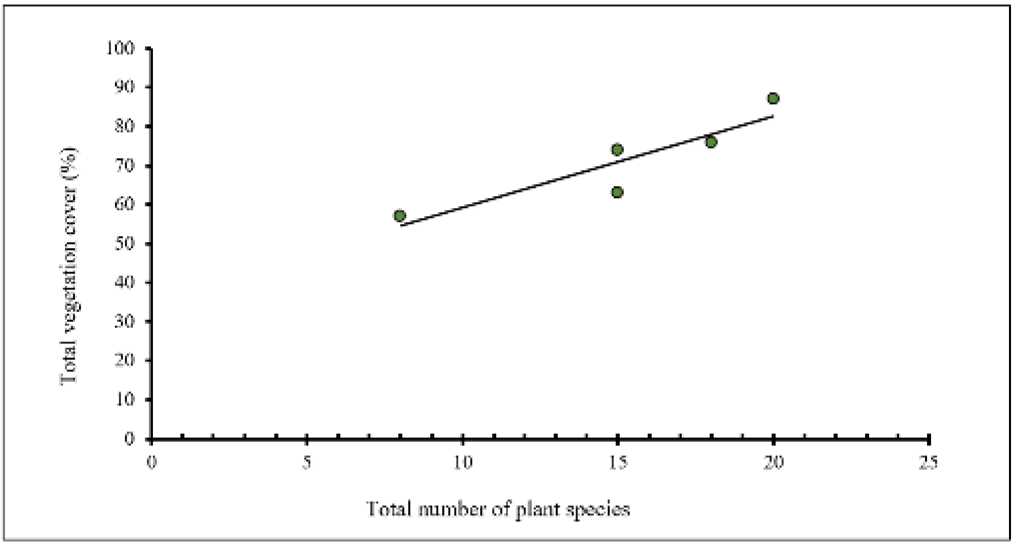

Figure 45. Linear regression for the relationship between total number of plant species and the total of the vegetation cover (%): Y=2.3261x + 36.043, R^2= 0.8157. This graph shows a statistically significant relationship between the total number of plant species and the total of the vegetation cover (%) from an analysis of repeat photography during post-fire months after April 2016 to January 2017 at Silvermine Nature Reserve (SNR).

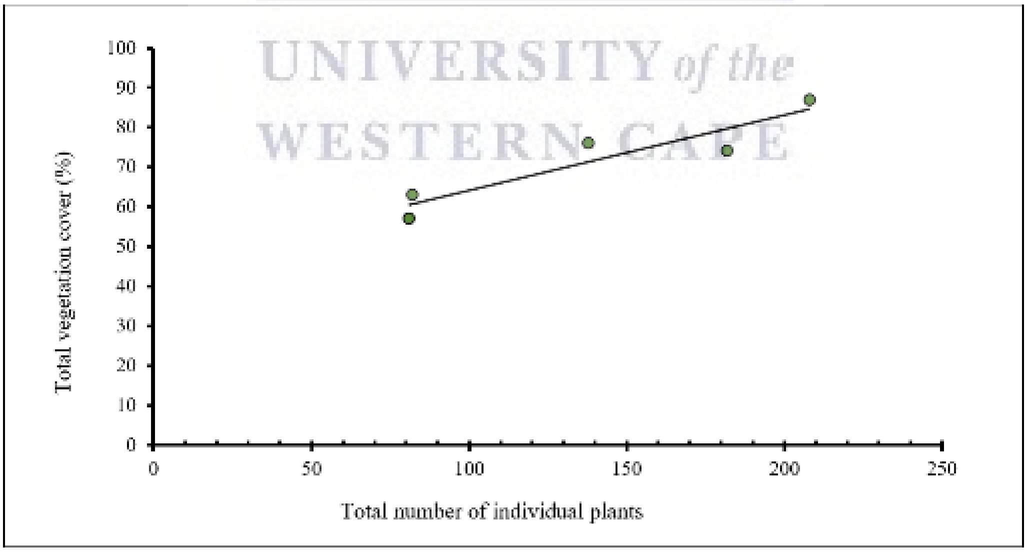

Figure 46. Linear regression for the relationship the total number of individual plants and the total of the vegetation cover (%): Y= 0.1889x + 45.292, R^2= 0.8591. This graph shows a statistically significant relationship between the total number of individual plants and the total vegetation cover (%) from an analysis of repeat photography during post-fire months after autumn 2016 to late summer 2017 at Silvermine Nature Reserve (SNR).

CHAPTER 6: DISCUSSION AND CONCLUSIONS

6.1 Examining Classical Field Techniques in Ecology for Monitoring and Evaluation

Ecological monitoring programs provide a quantification of the changes in landscape patterns and ecosystem species distributions (Bossier *et al.* 1990; Heinz and Tufford 2003; Niemi and McDonald 2004). These patterns can be assessed through classical field evaluation techniques using satellite and high-resolution air-borne imagery with fixed ground-based photography (Cherrill *et al.* 1995; Chytrý *et al.* 2011). Integrating satellite images with ground-based approaches are useful calibration tools for landscape monitoring (Frank and Thorn 1985: Landres *et al.* 1999: Vanha-Majamaa *et al.* 2000: Zhang *et al.* 2008; Chytrý *et al.* 2011). Vegetation classification and mapping are not only used to indicate the distribution of plant species but also the patterns of different plant communities (together with endemic and rare species). Such studies have contributed to the discipline of landscape ecology and practical aspects of biodiversity conservation (Taylor 1969; Mueller-Dombois and Ellenberg 1974; Bredenkamp *et al.* 1998; Rosentreter *et al.* 1999 Mucina *et al.* 2000; Černá and Chytrý 2005; Schwabe *et al.* 2011; Chytrý *et al.* 2011). Based on such data, which is recorded as cover-abundance, these can be used for monitoring changes in species composition and vegetation structure (Taylor 1969; Weber *et al.* 2000).

In this study, small 3 x 2 m fixed monitoring quadrats (Figures 9 and 10) was used to assess Mountain Fynbos recovery (Figure 7), at five sites arranged along an altitudinal gradient from 460 m to 626 m at SNR (Figure 8; Table 10). Using fixed-point images provided a very useful technique to visually assess plant biodiversity and phenological patterns in Mountain Fynbos. Although the initial setup of plot design for photographic analysis was difficult (Figures 9 and 10), very useful high-resolution fixed-point repeated parallel panoramic photography provided great detail of the regeneration of vegetation during the growing season in the present study.

6.2 Use and limitations of the Braun-Blanquet (B-B) Methodology

The Braun-Blanquet (B-B) is a commonly used method to describe plant assemblages (Brown *et al.* 2013). It is based on the estimation of the cover-abundance of plants within a measured quadrat (Taylor 1984). The use of the B-B methods in South Africa dates back to vegetation assessment undertaken in the nineteen-sixties (Werger 1973). This approach was especially useful for describing community structure in highly complex Mountain Fynbos vegetation (Werger *et al.* 1972, Werger 1973). Many studies were carried out using this technique in the CFR (Raup and Acocks 1955; Taylor 1969; Boucher 1977; Moll *et al.* 1984; McDonald 1985;

Campbell 1985, 1986). The Braun-Blanquet (B-B) methodology has been used to describe vegetation patterns and define plant communities (Clements 1916, 1928); understanding the relationships between plants and their environment (Gleason 1933; Whittaker 1962; Kent and Coker 1992); and assists with the preparation of environmental impact assessments (Taylor 1969; Moll *et al.* 1984; Taylor 1984). Braun-Blanquet together with climate change studies will contribute to making informed decisions on biodiversity management including clearing of alien plant species, developing a wildfire policy, and provision of shelter and food for wildlife (Rutherford *et al.* 2006; Skead 2011; Brown *et al.* 2013).

The Braun-Blanquet method is based on visual assessment of vegetation cover-abundance, frequency and density measurement and elucidating species-environment relationships (Wikum and Shanholtzer 1978). The vegetation data can be obtained by laying down adjacent quadrats of increasing size at permanent vegetation monitoring sites (Braun- Blanquet 1951, 1964; Killick 1966). All the plant species occurring in that assigned relevé quadrant can be listed in separate sections of the report and assessed to express the degree of presence of species or groups of species (Table 15) (Wikum and Shanholtzer 1978).

Consequently, my methodology observed that there was considerable variation in species richness, the number of individual plants (Table 14; Figures 15 and 16) and the total vegetation cover (%) (Figure 23) between study sites along an altitudinal gradient (Tables 14 and 10; Figure 8). So the lower and mid-lower altitudes had the most number of individual plants and diversity, mid altitudes had the lowest and the highest altitude had the second-highest species richness and the third in several individual plants (Table 14; Figures 15 and 16). However, there was an identical trend between the species richness (Table 14; Figure 15); and the number of individual plants at each season (Table 14; Figure 16). While, there was no total changes and no increase in species richness and the number of individual plants, so the number remained steady after the plant re-establishment in the first year of the post-fire at SNR (Table 14; Figures 15 and 16). The percentage of the vegetation cover has changed with a maturity growth peak of over 20% at each study site from autumn 2016 to late summer 2017 (Figure 23).

The main operational issues within the B-B methodology are the scales (abundance/ dominance scale is r, +, 1, 2, 3, 4 and 5) by which species cover is measured within each relevé quadrat (Podani 2006; Brown *et al.* 2013). The presence of non-number values of r and + (Table 15) excludes the possibility of conventional quantification methods (Van der Maarel 1979). Cryptic species are not used within the B-B methodology as they would overly influence the analysis depending on their presence or absence and other taxonomical problems (Brown *et al.* 2013). Many studies have shown how important plant phenology is (Wicht 1948; Van Rooyen *et al.* 1979; Gill 1981; Pierce and Cowling 1984); but there is difficulty in using B-B methodology for undertaking phenological studies. Many plants may not be identifiable for reasons such as not possessing flowers or fruiting capsules or being represented by small plants or seedlings or that the plants are dormant such as geophytes (Brown *et al.* 2013). While B-B methodology does not include quantification of certain assemblages such as annuals and geophytes, which may be the most important components to characterising the community or having important functional roles for herbivores, pollination and seed dispersal agents.

Table 15. The Braun-Blanquet cover-abundance scale (Mueller-Dombois and Ellenberg 1974):

Braun-Blanquet scale	**Cover value**	**Range of cover (%)**
R	Very rare	< 1 %
+	Present but not abundant and with a small cover value	1 %
1	Covering less than 1 % or not so abundant, but covering 1-5 % of the quadrat area.	1-5 %
2	Very numerous and covering less than 5% of the quadrat area, or covering 5-25% of the quadrat area independent of abundance.	5%
3	Covering 25-50% of the quadrat area independent of abundance.	25-50%
4	Covering 50-75% of the quadrat area independent of abundance.	50-75%
5	Covering 75-100% of the quadrat area independent of abundance.	75-100 %

6.3 Raunkiaer's Life Forms Classification

The identification of all species within a B-B study may present problems, therefore various alternatives should be considered (Werger 1973; Simmons and Cowling 1996; Ojeda *et al.* 2001; Brown *et al.* 2013). One alternative is to group species into different functional categories (or classes) with a similar set of characteristics (Batalha and Martins 2002). The relationship of plants to their environment may allow the classification of plants into different Life Forms (Mueller-Dombois and Ellenberg 1974). One of the first of such classification was Raunkiaer (Raunkiaer 1934).

The Raunkiaer system classifies plant species into five major classes, namely: *phanerophytes, hemicryptophytes, chamaephytes, therophytes* and *cryptophytes* (Raunkiaer 1934; Mueller-Dombois and Ellenberg 1974). His classification is based on the degree and position of protection of the plant buds and the regeneration during the growing season (Raunkiaer 1934; Begon *et al.*1996).

The system allocates a plant species to one of the five classes and these effectively form a new taxon of grouped species. This allows for a functional understanding of plant-environment dynamics and to broadly identify different plant guilds in the landscape. Based on the relationships between different Raunkiaer classes and the environment the impact of disturbances such as fires can be assessed (Godron *et al.*1969).

Many studies have linked Raunkiaer's life forms with climatic regions of the world (Cain 1950; Cain and Castro 1959; Shimwell 1971). Life forms have been used as a descriptive method for classifying vegetation forms within plant communities (Feoli-Chialpella and Feoli 1977; Holland 1978; Tyler 1979; Whittaker *et al.* 1979) as well as classifying ecotypes, biomes and the recognition of vegetative zones along altitudinal gradients (Allen 1937; Buell and Wilbur 1948; Cain *et al.* 1956; Beaman and Andresen 1966; Cain and Castro 1959; Shimwell 1971; Meuller-Dombois and Ellenberg 1974). Life forms have been used for predicting survival mechanisms of understorey and overstorey plant species in post-fire Mediterranean ecosystems (Raunkiaer 1934; Cain and Castro 1959; Naveh 1973, 1975; Chapman and Crow 1981).

My high-resolution fixed-point repeat parallel panoramic photography was capable of capturing imagery that represents various plant growth forms such as herbaceous, shrub, geophytes and succulents, from 3 x 2 m fixed monitoring quadrats (Figures 21 and 22). Since Fynbos is defined as Mediterranean shrubland (Moll *et al.* 1984) as well as, characterized by high species richness, endemism and classified as the most diverse dynamic ecosystems in the world (Cowling *et al.* 1996; Goldblatt and Manning 2002). This approach observed that sites with the greatest species richness are dominated by the greatest number of individual shrubs (Table 14; Figures 15 and 21). So the results showed the mid-lower altitude that has the most amount of plant diversity is dominated by the greatest number of individual shrubs and the highest altitude that has the second-highest species richness is dominated by the second greatest number of shrubs (Table 14; Figures 15 and 21).

This methodology recorded and tracked the leaf growth development of the plant growth forms individually, from the mature leaf stage until senescent leaf stage (Figures 29 and 30); Also, it evaluated the annual cycle health of the individual plants and identified when each plant died back and became senescent during post-fire months (Figures 17; 18; 19; 29 and 30 D). Repeated parallel panoramic photography recorded that autumn 2016 was the only season in which the leaf initiation stage (Figure 29) occurred. Autumn 2016 and winter 2016 were the only two seasons had a significant amount of number of individual plants with young leaves (Figure 29). Most of the plants leave matured from spring to early summer of 2016 and continued by a decrease that occurred in late summer 2017 (Figure 29). By late summer 2017, most individual plants had finished growth, their leaves had died back and became senescent (Figures 29 and 30 D).

6.4 A Novel Method for Managing the Biodiversity of Mountain Fynbos Ecosystem

Fixed-point repeat photography (FPRP) has been used as a tool to investigate the long-term changes of archaeological features, perceptions of change of land-use and wildfire patterns, changes and recovery (Powell 2013). This technique has been widely utilized in biodiversity conservation and environmental monitoring (Hoffman and Rohde 2010; Webb 2010; Powell 2013).

Regions with complex plant species assemblages such as Mountain Fynbos will require more detailed monitoring and evaluation methods that can be derived from B-B methods. Such complex systems present problems of having sufficient in-field taxonomic skills. Without possessing detailed taxonomic understanding such complex systems will require taking a lot of voucher specimens, which will then need to be identified through taxonomic keys or by use of Herbarium records.

6) Can high-resolution digital photography replace the classical phytosociological technique such as Braun-Blanquet cover-abundance estimates?

The traditional monitoring methods should be updated to improve the ability to better manage complex and species-rich ecosystems. This will require moving from the blunt instrument that B-B represents to a more fine-tuned toolbox of monitoring and evaluation. The only way to transition to a toolbox will involve acquiring more information collected with greater resolution. Photographic methods are the only mechanism to achieve this goal.

In the pursuit of developing a finely tuned toolbox, an FPRP was proposed in this study. Specifically, the toolkit should include a more inclusive and comprehensive monitoring of plants. This should include observation of plants with pronounced *annual* or seasonal cycles such as geophytes and annual plants that typically peak in spring.

My high-definition fixed-point repeated parallel panoramic photography represents solutions to reduce the limitations encountered in the traditional field techniques such as the B-B. This could be used to examine seasonality and changes that might be induced by climatic changes. Further, when used with fixed monitoring quadrants, this technique photographically recorded a significant amount of data relating to species richness and a number of individual plants (Table 14; Figures 15 and 16), structural assemblages (Figures 21 and 22), the percentage of vegetation cover (Figure 23) and phenological characteristics (Figures 31 and 38). In addition, it can record the onset of reproduction, their lengths (Figure 42), changes in leaf development and health as reflected by greenness (Figure 29) and other pigmentation (Figure 31) and the success of this reproduction including the number of seeds produced (Figure 38). Collecting such information can indicate any seasonal shifts in response to climate changes and detecting early signs of potential environmental stress. This is an important consideration for the maintenance of future biodiversity and has broad implications for defining major changes in plant community structure. Estimates of plant growth rates of all plants, the seasonality of the growth and that reductions of growth periods could be a precursor of unfavourable environmental conditions.

I have identified the four photography problems that this thesis will address systematically, namely:

1. Environment (weather condition).
2. Image resolution.
3. High Dynamic Range (HDR) and Image Exposure corrections.
4. Perspective and distortions.

6.4.1 Environment (weather condition)

Weather conditions will cause variations in natural light, which in turn can induce shadows. Natural lighting varies with the degree of cloudiness and the time of day and season. This is due to the height of the sun and the need for optimal photography, which requires the sun to be maximally overhead. Summer seasons and midday provide the best overhead lighting which minimizes the shadows. Shadows in photography represent a loss of data quality.

To avoid lighting problems no photography was undertaken if there was more than 5% cloudiness. To keep the sun as overhead as possible, my photography was limited to 11h00 and 14h00 hours. The quadrats were permanently marked and the position of the camera to the quadrat was fixed to ensure the photographs had as consistent exposure as possible. Since leaves are often shiny and cause glare, the camera lens was equipped with a Hoya 72 mm NXT Circular polarizing filter. By polarising the light bright spots of reflected sunlight were significantly reduced (Matiash 2015).

6.4.2 Image resolution

Typically, Digital Photography simply does not provide sufficient pixel resolution for the required detail that monitoring and evaluation programmes require. Although the pixel count continues to progressively increase, this does not necessarily translate into better quality imagery. A case in point is that the Xiaomi mobile phone provides for a 108 Megapixel image (Gil 2020); but since the pixels are oversampled and the image capturing sensor is small the resulting image while good for a mobile phone is very inadequate for purpose of monitoring and evaluation. Consequently, a sufficiency of pixels does not fully resolve the resolution problem which can only be addressed by using a large camera sensor. The two options available are the full-frame DSLR or the Medium Format Digital Cameras. The larger sensor size of medium format cameras should provide better information, but they are double the cost (more than ZAR 100 000) and have a very limited choice of cameras. A further problem was the data transfer from the CCD sensor to the storage card rendered image capture as slow. At the time of project planning, only a 50 Megapixel Fuji GFX 50, which has subsequently been updated with a 100 Megapixel body (Fuji GFX 100) became locally available in 2020 (George 2020). For this study, I used the then-current highest pixel count DSLR camera, a Canon 5DS R, which captures an image of 8688 x 5792 pixels (50.6-megapixel) (Brawley *et al.* 2015). This option was half the price of the medium format cameras, and there is a much wider choice of lenses. The significance of the latter is that I could deploy a tilt and shift lens. The combination of the full-frame sensor with the high pixel count, however, still provides insufficient details for monitoring and evaluation.

The ability to attach the Canon TS-E Tilt-Shift Lens great enhances the ability to capture pixels for improved final image resolution (Greengo 2014). By orientating the camera in a portrait mode and then using the full range of the shift facility (extreme left, middle and extreme right adjustments) three images are taken which effectively extends the field of view of the camera (Figure 11). The three separate images were post-processed using Adobe Photoshop CC and Lightroom to generate a new stitched parallel panoramic image a resolution of 11092 x 8565 pixels (Figure 13). As of 2019 only the Fuji GFX 100 and Hasselblad H6D-100c Medium format cameras can achieve a similar resolution. Software updates of both the Fuji GFX 100 and Hasselblad H6D-100c can increase the resolution to 400 megapixels using a multi-shot pixel shift technology (George 2020). This technology will not be feasible for a reason to explain under the Dynamic Range Problem. Even when using such some high-resolution image capture platforms, the size of the quadrat needs to be smaller than are typically used when a B-

B approach is used. In Mountain Fynbos, the typical quadrat size is 5 x 10 m. I reduced the quadrat size to 3 x 2 m to ensure I could collect data with sufficient resolution. The use of a small quadrat size in highly complex and species richness ecosystems aligns with the studies of Mustart 1993; Elzinga 1998; Warmink 2007; Straatsma *et al.* 2008; Bring 2009.

6.4.3 High Dynamic Range (HDR) and Image Exposure corrections

As previously explained, there are many changes in the seasonal weather conditions during the sampling period (autumn 2016 – late summer 2017). There were variable changes in image exposure such as bright or shadows spots, that caused difficulties to re-photograph the sites and maintained constant of RGB colour channels. Under such circumstance, the usual recommendation is to take multiple exposures (under and overexposed) and combine all the exposure to form an HDR image. Using the exposure bracketing (Debevec 2008; Cohen *et al.* 2001; Brown 2006; Cox and Booth 2009), will result in images containing greater details both in the shadows and in the bright spots of the image.

I was not able to create HDR images using exposure bracketing due to two issues. The image being photographed has many small objects such as leaves, flowers and fruiting capsules and as a consequence, the number of edges in the image is very high. All the edges will all need to correspond across the different exposures to properly generate the HDR image. For normal landscape images, these issues rarely become a problem due to optimised algorithms. In our case, the very high captured detail with all of its edge effects together prevailing conditions of wind made the HDR images somewhat unclear and difficult to process. Although photography was conducted under as windless conditions as possible (typically less than 10 km/h) the problem was not resolvable. It is, for this reason, a multi-shot pixel shift technology described for the Medium Format Cameras where a 100 Megapixel image can be upgraded to a 400 Megapixel image does not work. I explored this technology using an Olympus OM-D E-M1 Mark II. The normally 20 Megapixel OM-D E-M1 Mark II can acquire images of 50 Megapixel by shifting the image sensor by 0.5-pixel movements and taking eight images (Lawton 2017). These images are merged into one 50 Megapixel image. To obtain images for monitoring and evaluation the resulting images were not of sufficiently high quality for reasons similar to the use of HDR procedures, namely the combination of slight wind and high edge effects.

The only way to overcome the exposure problems is to use HDR Toning in Adobe Photoshop CC (Evening 2014). I used HDR Toning in Adobe Photoshop CC to enhance detail in bright spots and shadows (Figure 14) (Evening 2014).

When capturing the images, I used six colour calibration RGB boards for radiometric colour correction (Figures 9 and 10). This allows the images to have colour corrections adjusted from the environmental conditions using the known colours from the RGB colour boards. Then

I used the match colour tool in Adobe Photoshop CC to match (8 bit) RGB colours channels between multiple images (Evening 2014), and this allowed images taken at different times and seasons to be colour matched so that the detail obtained from the images was near identical. Several methods can be used. I found the best method was to take the 8-bit RGB colour channels and transform into HSL using Adobe Lightroom (Evening 2015). Images were further improved by adjusting colour warmth with a small amount of image sharpening, contrast adjustment and noise reduction filters (Table 13) (Evening 2015; Morganti 2015a). These adjustments were made by inspection and by comparing each of the images taken across the different seasons.

The technique was able to record and classify the predominant leaf colour conditions and the phenological development of the growth forms during post-fire months (Figure 31) which included: mostly green or brown leaves (Figures 32 A and B), light green (Figure 33), pigmented (a mixture of orange, red or dark magenta pigments) (Figures 34; 35 and 36) and transitional leaf colours (mixed green and yellow pigments) (Figure 37). Autumn 2016 was the season with the highest number of individual plants with predominantly green leaves (Figure 31). Some individual succulents were mostly green during the initial growth in autumn (Figure 31), while during winter 2016, these succulents developed red pigments to their leaves (Figures 31 and 35). From autumn to spring 2016 some individual shrubs matured their leaves to a light green colour (Figure 33). Some herbs pigmented their leaves from green to a dark magenta pigment (Figure 36). During the summer drought (November 2016 – January 2017), some shrubs, herbs and geophytes had finished their growth and pigmented their leaves to transitional colours (mixed green and yellow pigments) (Figures 31 and 37) while some individual plants of these growth forms were still mostly green and had no change in the leaf colour (Figure 34). This is explained by plants have finished their growth and their leaves had died back and turned brown (Figures 31 and 32 B).

The high-resolution fixed-point repeat parallel panoramic photography clearly tracked the blooming stages and seed production of the individual plants during the entire sampling season (Figures 38 and 40). In autumn 2016, geophytes were still retaining the old flower heads, some herbs were still retaining the old sepals (calyx) but when it was a small seedling, even after these growth forms lost their petals from the last blooming, over more than 14 months after the fire of February 2015 (Figures 39 A; B and C). The images were also able to identify herbs that had full blossoming followed by leaf development after the flowering had finished (Figures 41 A and B).

Many shrubs had not matured sufficiently in the 21-23 months' post-fire and consequently had not flowered by the end of the study period (Figure 38). Most growth forms had started to produce the flower buds (flower initiation) from autumn and peaked in spring 2016, by which time they had matured into full blossoms 14-19 months' post-fire (Figure 38). Flower initiation continued but declined through summer months for both shrub and herb species (November 2016 – January 2017). Most plants species had flowered and finished blooming by the summer months (November 2016 and January 2017). The great majority (80 %) of all growth forms had flowered by early summer 2016 and 60% had finished flowering and became senescent by late summer 2017 (Figure 38).

6.4.4 Perspective and distortions

There will also be some compromise when attempting to take a three-dimensional real-world situation into a flat two-dimensional image and consequently distortions are inevitable. This becomes even more of an issue if you are wishing to calculate measurements from the image such as determining plant growth rates and plant heights. Photographs taken directly overhead such as Landsat Imagery do not have significant distortion and where it exists, it is limited to the edges. Taking photographs directly overhead needs either complicated overhead apparatus or the use of a drone with sufficient payload to carry a two kg camera set up. Generally, the use of drones is not permitted in Protected Areas. It is unlikely that SANParks would have issued the necessary permits for us to use a drone.

The second issue with taking photographs directly overhead is that you can only record the overstorey vegetation. All understorey vegetation will be hidden from the camera's sensor. It is for this reason that side-ways imagery will allow determination of overstorey and understorey vegetation, as well as estimating height and, with repeat photography, growth rates. Inevitably, taking sideways images results in distortion of dimensions and perspective. This is inevitable since objects closer to the field of view of the camera will appear larger and as they get further away they will appear to be smaller.

To ensure the angles of view (field of view) are maintained relative to the quadrat, I used a Canon TS-E 45mm f/2.8 Tilt-Shift Lens to reduce errors of distortion within the sampling quadrat relative to the image sensor (Greengo 2014). The quadrat is designed with a fixed tripod position (4m away) and height (1.6 m) and at a pre-specified direction (Figures 8 and 9).

To further enhance the accuracy a triple-axis bubble spirit level was used to keep the camera level relative to the ground (Picker 2014; Izzy 2015).

Due to the way natural light is transmitting into the camera lens's glass, camera lenses can display various kinds of disadvantages at certain focal distances, f-stops and focal lengths (Judge 2013; Hull 2020). Before taking any imagery the camera set up was tested under studio conditions to optimise the correct setting for the f-stop. This allowed for the sharpest imagery possibly to be maintained. DSLR are typically equipped with a low-pass filter that reduces false colours and the generation of moiré patterns but this does reduce resolving power of the sensor. As a consequence, I used the Canon 5DS R, which cancelled a low-pass filter to produce both greater sharpness and finer detail. This was necessary given that we wish to identify and measure extremely small objects within a relatively large scene. This was the recommendation of the camera manufacturers for high-detail applications. This process of optimising the f-stop or aperture opening also reduces the problem of chromatic aberration. Chromatic aberration is also known as purple or colour fringing and is the failure of a lens to focus all colours onto the same point and manifests itself as fringes of colour along edges. Almost all camera-lens setups will incur some aberration although it can be controlled through optimising the aperture settings and post-processing (Mallon and Whelan 2007; Zawadzki *et al.* 2008; Evening 2015). This colour fringing along the edges of image objects is especially noticeable in high-contrast subjects, such as reflections from shiny surfaces such as leaves which are designed to scatter the light (Mansurov 2019).

Careful planning in the photographic set up largely eliminated chromatic aberration from my images Other distortions include vignetting causes darkening at the edges and in the corners of an image (Evening 2015; Mansurov 2019). The process to reduce colour aberrations will also reduce vignetting issues. The use of a fairly standard 40 mm focal length also minimizes the possibilities of vignetting. Since my images are focused on the centre of the scene and the processing of stitching uses quite large areas of each of the three images to produce the panoramic image both a colour aberration and vignetting were kept to a minimum in the image capture process.

No matter what lens is used optical aberrations will occur. These distortions are induced by rectilinear projections which try to keep the lines in a straight scene. This manifests itself into two types of distortions, namely barrel and pincushion. Barrel distortion is most common in wide-angle lenses or telephoto lenses used at their widest focal length, causes straight lines to bow outward at the edges of the image (Evening 2015; Grigonis 2020). Pincushion distortion is almost the opposite effect and commonly happens at the telephoto end of a zoom lens. This is due to the higher magnification at the edges of the image which causes distortions of straight lines which bend inwards from the edges of the image (Evening 2015; Mansurov 2019).

Every effort was made to reduce all these types of chromatic and optical aberrations. This situation can be further improved in the post-processing of imagery. There are steps in image post-processing were these can almost be entirely eliminated. In Adobe Lightroom there is a lens correction tool (Morganti 2015a) and this was applied to all three images individually, before merging them to create the final panoramic image.

Although every effort was made to ensure that the camera sensor was placed in the exact position relative to the quadrat, the images still needed a manual correction so the locations of each plant could be matched with each other across the five images representing the different seasons. This is analogous to the geometric correction of aerial photography. A grid was used which divided the 3 x 2 m quadrat into 24 sub-cells (Figure 10). This grid could be matched across the different images using a rubber sheet method. In Adobe Photoshop CC the image warp tool could be used for this procedure (Evening 2014).

This methodology recorded and tracked the leaf growth and development of the plant growth forms individually, from the mature leaf stage until senescent leaf stage (Figures 29 and 30). The methodology also allowed for the evaluation of the annual cycle health of the individual plants and identify each plant and its life cycle (Figures 17; 18; 19; 29 and 30 D). Repeated parallel panoramic photography recorded that autumn 2016 was the only season in which the leaf initiation stage occurred (Figure 29). Autumn to winter 2016 had a significant amount highest of the number of individual plants with young leaves (Figure 29). Most of the plant's leaves matured from spring to early summer of 2016 and decreased from late summer 2017 (Figure 29). By late summer 2017, most individual plants had finished growth, their leaves had died back and become senescent (Figures 29 and 30 D).

These methods developed in this study were able to estimate the heights of individual plants across different life forms using measurement height sticks (Figures 9; 42 and 43). At the onset of the study, many plants represented in several growth forms such as shrubs, succulents, geophytes, and herbs were still small (≤ 50 mm). Maximum growth occurred in autumn 2016 in the first year of post-fire (Figure 42). From winter to spring 2016, some plants of shrubs, succulents and geophytes increased their height from 50-250 to 250-500 mm (Figures 42 and 43). Also, some individual plants of geophytes and herbs increased in height from 250-500 mm to 500-1000 mm while some individual geophytes died back and effectively moved from a height of 500-1000 mm to heights 250-500 mm (Figure 42). During the summer drought (November 2016 – January 2017) some geophytes had finished their growth, the leaves had died back and shorting their height from 500-1000 mm to 250-500 mm (Figures 20; 30 D; 32 B and 42).

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