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Wildlife activity patterns and encroaching woody vegetation response to bush thinning on farmlands in north-central Namibia

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Academic dissertation
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ABSTRACT

The Namibian savannah ecosystem has experienced considerable anthropogenic pressures, which have resulted in the disruption of key ecological processes, and consequently, the proliferation of a dense vegetation structure, commonly known as bush encroachment. Approximately 45 million hectares of land have been affected, which has caused a significant decline in the grazing capacity, poor economic returns for the farmers, and loss of suitable wildlife habitat. Restoration thinning, a method that involves the selective removal of excess trees/shrubs, has been applied to counteract the negative effects associated with this phenomenon.

This thesis aimed to assess the effect of thinning on (a) the activity patterns of local ungulates and predators, (b) the encroaching woody vegetation in terms of (i) regeneration, and (ii) structure, abundance, and habitat sighting lines, in a savannah habitat in the north-central region. Generalised linear mixed-effects models (GLMM) and linear mixed-effects models (LME) were used for statistical analysis. Results showed that thinned areas had overall greater wildlife activity. Thinned areas also had reduced tree/shrub abundance, which was significant for the mature height classes. Natural regeneration was rapid in thinned areas, where the abundance of young cohorts was 34% greater than non-thinned areas. In the thinned areas, red umbrella thorn (*Vachellia reficiens*) was significantly reduced but umbrella thorn (*Vachellia tortilis*) numbers increased. Tree/shrub densities in the thinned areas fell within the commonly accepted range for a 400 mm rainfall area (600–750 tree equivalents (TE) ha^{-1}). Thinning significantly modified the dense thornbush to an open vegetation structure with a low woody canopy cover that favours grass growth and provides greater sighting lines for open savannah wildlife. This thesis demonstrated that thinning was effective in controlling bush encroachment and could be used as a method to restore other affected areas. However, periodic post-thinning management is recommended to control the established samplings.

Keywords: *Acinonyx jubatus*, bush encroachment, natural regeneration, rangeland degradation, restoration thinning, thornbush savanna

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Joensuu, May 2024

Matti Tweshiningilwa Nghikembua

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I-III. Articles are reproduced with the kind permission of publishers.

I Nghikembua, M.T., Marker, L.L., Brewer, B., Mehtätalo, L., Appiah, M., Pappinen, A. (2020). Response of wildlife to bush thinning on the north central freehold farmlands of Namibia. For. Ecol. Manage. 473, 118330. https://doi.org/10.1016/j.foreco.2020.118330

II Nghikembua, M.T., Marker, L.L., Brewer, B., Leinonen, A., Mehtätalo, L., Appiah, M., Pappinen, A. (2021). Restoration thinning reduces bush encroachment on freehold farmlands in north-central Namibia. For. An Int. J. For. Res. 1–14. https://doi.org/10.1093/forestry/cpab009

III Nghikembua, M.T., Marker, L.L., Brewer, B., Leinonen, A., Mehtätalo, L., Appiah, M., Pappinen, A. (2023). Response of woody vegetation to bush thinning on freehold farmlands in north-central Namibia. Scientific Reports. https://doi.org/10.1038/s41598-022-26639-4

Author's contribution

Matti Tweshiningilwa Nghikembua (Nghikembua M.T.) was the primary author of all the articles. He was responsible for the field work, data analysis and writing of all the articles. The experiments in all studies (Articles **I**–**III**) were planned together with Prof. Ari Pappinen, Adjunct Prof. Mark Appiah and Research Prof. Lauri Mehtätalo. Statistical data analysis was supported by Prof. Lauri Mehtätalo. All co-authors improved the quality of the articles through their revisions and comments.

TABLE OF CONTENT

LIST OF ABBREVIATIONS AND TERMS

AIDS	Acquired immunodeficiency syndrome
Ca	Calcium
CCF	Cheetah Conservation Fund
CO_2	Carbon dioxide
EC	Electrical conductivity
FSC	Forest Stewardship Council
GLMM	Generalized Linear Mixed Effects Model
ha^{-1}	per hectare
HIV	Human immunodeficiency virus
ind. ha^{-1}	Individuals per hectare
K	Potassium
km^2	Kilometre square
LME	Linear Mixed Effects Model
LOF	Landscape of fear
LSU	Large Stock Unit
m	Metre
mg	Milligram
Mg	Magnesium
mm	Millimetre
MT	Metric Tonne
MW	Megawatt
Na	Sodium
ºC	degree Celsius
OM	Organic matter
P	Phosphorus
pH	Potential of hydrogen
PTY LTD	Proprietary Limited
SD	Sustainable development
TE	Tree Equivalent
TN	Total Nitrogen
$year^{-1}$	Per year

1. INTRODUCTION

1.1 Background to the thesis

Woody plant encroachment (hereafter referred to as bush encroachment) has been reported in grasslands and savannah ecosystems across the globe (Archer et al., 2017; Kgosikoma and Mogotsi, 2015). This phenomenon is characterised by an increase in density and biomass of native and alien woody vegetation, which results in dense thickets with little grass cover and limited sighting visibility. Multiple drivers have been associated with this phenomenon, with the prominent factors considered to be herbivore management regimes (e.g. livestock grazing intensification, displacement of natural browsers and megafauna (e.g. elephants *Loxodonta Africana*) and seed predators), climate change (e.g. increase in the frequencies of droughts, and high rainfall variability) and fire suppression (Archer et al., 2017; García Criado et al., 2020; Sankey, 2012). In recent decades, considerable attention has been given to the impacts of this phenomenon, specifically on ecosystems services, the global carbon balance and the effects on livelihoods associated with physical tree/shrub removal (Birhane et al., 2017; Musekiwa et al., 2022; Stafford et al., 2017). Therefore, an exploration of the impacts associated with this phenomenon, as well as its control, are meaningful for biodiversity conservation and sustainable rangeland management. Studies of this nature could reveal the responses of the local flora and fauna, and the sustainability management actions that could be applied to mitigate the adverse impacts on these ecosystems.

Approximately 41% of the global land surface area is comprised of grasslands and savannah ecosystems. These ecosystems are also known as drylands, of which 69% are rangelands and support various land uses (e.g. pastoralism, tourism, wildlife) that are crucial to sustain livelihoods (Briske, 2017). Also, these areas support biodiversity outside of the protected area matrix. However, they experience limited primary productivity due to low rainfall and soil water, as well as high rates of evapotranspiration. Degradation of drylands, including bush encroachment, is defined as the loss of rangeland productivity, which has been identified as a major problem that affects most southern African rangelands (Inman et al., 2020; Li et al., 2021; Stafford et al., 2017).

This phenomenon (encroachment) has been reported in grassland and savannah biomes since the latter half of the 20th century and corresponds to increasing atmospheric carbon dioxide (CO_2) concentrations and temperatures, as well as reduced rainfall (Archer et al., 2017; Venter et al., 2018). Over the last three decades, differential rates of woody cover increase have been observed in different regions across Africa, with the greatest (>30%) observed in the central interior and in areas with moderate initial woody cover, with less gains (~3.5%) across shrublands (Venter et al., 2018). Such an increase has been attributed to the greater efficiency of woody plants (C_3 photosynthetic pathway) at utilising elevated atmospheric CO_2 levels under warmer conditions than grasses (C_4 photosynthetic pathway) under similar conditions (Archer et al., 2017; Higgins and Scheiter, 2012).

Land degradation is a concern for southern Africa, especially as this region continues to experience environmental pressures that have arisen from human activities (e.g. deforestation, overgrazing, soil degradation and habitat alterations), in combination with high variability in climate conditions (e.g. rainfall, warming and drying), which promote water stress, limited primary productivity, loss of habitat, range contraction, and reduced abundance of some native fauna and flora (Kapuka and Hlásny, 2021). This is unfortunate since it increases risks and vulnerabilities amongst the pastoral communities that are dependent on seasonal rainfall for grazing and water (Samuels et al., 2022). Also, southern Africa is home to the world's largest free-ranging cheetah (*Acinonyx jubatus*) population (~4000 adults and adolescents) that are found mainly in landscapes affected by bush encroachment (Marker et al., 2018b). Therefore, loss of suitable habitat, compounded by climate effects, are likely to limit the abundance of favourable prey, which could cause further decline in cheetah populations (Marker et al., 2018c). Restoration of encroached rangelands to open savannah structure as an adaptation strategy could provide benefits to landowners by increasing the grazing capacity and suitable wildlife habitats, and thereby boost prey populations and increase farm profits through biomass utilisation, ecotourism and livestock farming.

1.2 Overview of bush encroachment and woody biomass utilisation in Namibia

Namibia is a country in south-west Africa with a total land area of approximately 824,268 km^2, and a population of ~2.3 million people (2010 census estimate) (Ruppel-Schlichting, 2016a). Approximately 45 million hectares of the territory is affected by bush encroachment, which has resulted in loss of grazing capacity and annual economic losses of approximately N$2.7 billion in the livestock industry (SAIEA, 2016). This phenomenon is understood to have intensified following a decade (1948–1958) of above average rainfall and high livestock stocking rates, which led to decline in grazing capacity in certain areas by as much as 100% (from 10 hectares (ha) for 1 Large Stock Unit (LSU) to 20–30 ha for 1 LSU year^{-1}) (de Klerk, 2004; MAWF, 2012). This phenomenon has negatively affected livestock farming, which is one of the key sectors of the national economy, and most of the population (70%) is directly or indirectly dependent on natural resources for sustenance (NPC, 2017).

Despite these negative consequences on grazing, there are benefits to people from bush encroachment, such as the utilisation of the woody biomass for energy purposes (e.g. cooking and heating, thermal energy), and the production of animal feeds, especially during drought periods. As Namibia experiences variable rainfall periods, the bush feed is valuable during droughts because of the lack of grazing, and it is produced by local farmers to supplement livestock feeding. Over the past decade, considerable interest has developed at the national level to intensify biomass harvesting efforts to restore rangeland productivity and increase farmland profits (NPC, 2017). Simultaneously, there has been much interest in how the encroaching woody biomass could be utilised and how the increased use of such biomass could affect the woodland, its biodiversity and carbon stock (SAIEA, 2016).

Traditionally, charcoal has been the most dominant form of commercial biomass utilisation, estimated to have been in existence for over three decades (MITSMED, 2017). Concurrently, it is the most developed agricultural subsector, with annual production estimated to exceed 120,177 tonnes year^{-1} of which the majority (>60%) is exported, mainly to South Africa and Europe (Beck, 2020). Encroaching woody biomass is also utilised in its natural form as firewood, fencing posts, and in the construction of houses and animal enclosures. It has considerable potential as a replacement fuel, especially in deforested areas that face shortages of this resource. In 2019, production of firewood from encroaching plant species was estimated at approximately 120,000 tonnes, with the firewood used mainly for domestic consumption. Sales of firewood were slightly above 50,000 tonnes (Beck, 2020).

Wood fuel briquettes (BUSHBLOK®) produced from chipped wood for cooking and heating, were introduced by the Cheetah Conservation Fund (CCF)'s Bush Project PTY (LTD). This project was initiated in 2001 to restore rangeland productivity and habitat for local biodiversity. The cheetah was used as an umbrella species to demonstrate to other biomass users that harvest technologies can be environmentally friendly (CCF, 2019; Wykstra et al., 2018). The production of animal feeds from encroaching woody plants, locally known as bushfeed, has also been done through the harvest of leafy bushes with smaller stem diameters (≤ 2 cm), which are easier for livestock to digest (Beck, 2020; Honsbein et al., 2017b). A recent interesting development is biomass-powered electricity by Namibia Power Corporation (NamPOWER). In 2018, NamPOWER completed a feasibility study for their proposed biomass power plant in the Otjikoto region with a capacity of 20 MW (updated to 40 MW in 2021) with a 25-year lifespan (Brown et al., 2018). The annual energy requirement for this power plant is approximately 200,000 tonnes dry woody biomass, which will be sourced within a 100 km radius from the surrounding farmlands. It has been estimated that an adequate supply of dry woody biomass is available in the area (~48.7 million tonnes), so the fuel requirement over the entire operational period represents only 10.8% of the available woody biomass.

Another recent interesting development is the utilisation of encroaching woody biomass as a replacement fuel to generate thermal energy in industrial kilns with the goal to reduce coal consumption. The Ohorongo cement factory, located in the Otjikoto region of the country, has been the main consumer of wood chips (~85,000 tonnes year $^{-1}$) sourced from surrounding farmlands, although due to supply constraints, only 50% of this demand is currently met (Beck, 2020). In addition, Namibia Breweries, located in the capital of Namibia (Windhoek), utilises ~7500 tonnes woody biomass year^{-1} for thermal energy (Birch and Middleton, 2017).

Namibia has a combined 489.5 MW of installed capacity: The main sources of power consist of the Ruacana hydro-electric plant at 347 MW (variable), the 120 MW thermal coal-fired Van Eck Power Station, and the 22.5 MW standby diesel-driven Power Station at Anixas, Walvisbay (NamPOWER, 2021). On average, 50–60% of the country's electricity demand (annual demand = 673 MW) is imported, with the majority sourced from Eskom, a power utility in South Africa (NamPOWER, 2021). Electricity is one of the main energy resources required for socio-economic development, so a sustained supply, especially from different sources that include encroaching woody biomass, is crucial for the country's economic growth, which is expected to increase the demand for energy in the near future.

Various strategies have been applied to control bush encroachment, such as physical tree/shrub removal, as well as chemical and biological control. The manual method is the most commonly applied in small-scale operations, and involves the physical manual removal of trees/shrubs with handheld tools (e.g. axes, mattocks, hand saws, machetes) (DAS, 2017; Trede and Patt, 2015). The advantages of this method include its low investment costs, reliance on unskilled labour, greater control over the selection of target species and sizes, and minimal disturbance to soils and the environment (Birch et al., 2016; Trede and Patt, 2015). Intensification of this method would be ideal for job creation. However, there are some concerns amongst the Namibian farming community with regard to the low production output and the employment of larger teams since they carry potential social and environmental risks that include poaching, social disruption, disease transfer (e.g. Human immunodeficiency virus (HIV-AIDS)), and the required provision of amenities (Birch and Middleton, 2017).

The semi-mechanised method involves labour with small, powered handheld tools (e.g. brush cutters, chainsaws and trolley saws). In comparison to manual control, this method is more efficient with less unit costs and higher productivity (DAS, 2017; Leinonen, 2007). The disadvantages of this method include difficulty in manoeuvring the equipment, especially in dense vegetation, which may require more than one person per equipment, adequate skills to operate the equipment, as well as health and safety risks while operating the equipment (e.g. noise and smoke pollution, fatigue) (DAS, 2017; Leinonen, 2007).

Mechanical control involves the physical removal of trees/shrubs by means of self-propelled heavy machines (e.g. bush rollers, bulldozers, skid steer, front end loaders, forestry harvesters, excavators), fitted with harvesting attachments (e.g. rotary saw, or harvester head). This method is ideal for large-scale operations due to its high productivity; however, highly trained operators and supervisors are required to ensure environmental compliance (e.g. correct species and sizes are selected) (DAS, 2017; Leinonen, 2007). However, this method could potentially disturb soil and ground cover, and there are also difficulties in avoiding slow-moving ground dwelling faunal species (Birch et al., 2016; Trede and Patt, 2015). The control of bush encroachment with roller choppers has been shown to have short-lived effectiveness (10 years), with several significant alterations to the vegetation structure, such as the dominance of shorter plants possibly due to resprouting or seed fall; and to the composition of ground-storey plants through increased forb cover and reduced grass cover (Eldridge and Ding, 2021).

The chemical method involves the use of approved arboricides (e.g. Picloram, Glyphosate) that are applied to freshly cut stems and foliage, and as soil applications near the stems of the target plants. They can be applied as a primary treatment in areas where other methods are impractical to implement due to high tree/shrub densities (>2000 ind. ha^{-1}), or as an aftercare treatment to suppress regrowth of harvested stumps (DAS, 2017; de Klerk, 2004). In high tree/shrub density areas, aerial application would be the most practical option, although this type of control is prohibited under Namibia's Forest Act 12 of 2001 (amended in 2005), and prior approval is required (Namibia, 2001). This is because aerial application is non-selective and has been shown to cause significant mortality of non-target trees/shrubs (including mature individuals), and lead to the loss of woody vegetation structural diversity that can affect habitat suitability for a range of species (Dreber et al., 2019). However, if applied selectively, chemical treatment is preferred since it restores encroached areas to well-structured and open savannahs with an ideal grass cover that is beneficial to both livestock and wildlife (Harmse et al., 2016; SAIEA, 2016). Despite these beneficial effects, uncertainties with regard to potential long-term side effects of the use of arboricides in the savannah ecosystems exist and requires further research (Dreber et al., 2019).

The biological method involves the use of natural factors, such as browsing pressure (game, domestic browsers), fungi, and fire to control bush encroachment The application of browsing pressure through the use of domestic goats (*Capra aegagrus hircus*) has been shown as an effective method to reduce densities of sickle bush (*Dichrostachys cinerea*) and non-encroaching palatable bushes with no effect on black-thorn (*Senegalia mellifera*) (de Klerk, 2004). This would suggest that the use of goats cannot be relied upon, especially since they are not effective for all encroaching species and have the potential to cause decline of non-encroaching palatable woody species. Also, most farmlands affected by bush encroachment are intensively used for cattle farming, thus, a significant change in the current farming practice accompanied by an increased effort to manage a small stock of goats at high stocking rates would be required. Another disadvantage to the use of goats is that they cannot be used as a primary control method in areas with mature dense vegetation but may be more effective as an aftercare treatment in smaller areas to suppress regrowth or sapling establishment (de Klerk, 2004).

The use of natural mega browsers, such as elephants, could play an important role in controlling bush encroachment, especially if reintroduced in their former ranges. Elephants are effective in the modification of the vegetation structure and their increased browsing pressure causes significant mortality amongst tree/shrub species and reduction in the overall densities (O'Connor, 2017). This type of control is relevant for Namibia since it can be an alternative option to mitigate human-wildlife conflict and reduce overpopulation. Fungi (e.g. *Cytospora chrysosperma*, *Phoma cava*, *Phoma eupyrena*, and *Phoma glomerata*) could also play an important role in controlling bush encroachment in the future, especially if further research is undertaken with regard to cost effectiveness and feasibility of the method. Fungi are known to promote natural die-off by causing extensive leaf sclerosis and stem wood decay amongst encroaching species (e.g. *Senegalia. mellifera*) (DAS, 2017; de Klerk, 2004; SAIEA, 2016)

Fires are important in maintaining open savanna vegetation structure. Hence, ongoing suppression has been linked to the increase in woody vegetation cover and abundance (Venter et al., 2018). In the absence of natural fires, prescribed burning can be an alternative management strategy to modify the woody vegetation structure and as an aftercare treatment following primary control to reduce seedlings and sapling establishment. Although benefits exist, fires are not popularly applied in Namibia as a bush encroachment control strategy due to their potential risks to grazing, woody vegetation, infrastructure and livestock, as well as the financial liability associated for any incident (Lohmann et al., 2014; Namibia, 2001).

As aforementioned, charcoal and firewood are the most common products in the biomass sector. Most biomass production for commercial purposes is found on freehold farmlands, where landowners have private title deeds. Thus, these landowners have the choice to engage in any commercial activity, dependent on available financial resources and expertise. However, recent developments have seen increased interest in the biomass sector, particularly in regard to other value chains, such as biomass electricity, biochemicals, biochar, torrefaction and animal feeds. Regardless of the value chain, all woody harvest operations in Namibia are regulated by a forestry and environmental authorisation process. This consists of the issuing of harvest, transport and marketing permits, and encompasses guidelines and procedures to be followed to comply with forestry laws.

Forestry harvest operations are expected to adhere to Forest Act 12 of 2001 (amended 2005), which aims to conserve forest resources (e.g. soils, water, fauna, flora) and ensure their sustainable use (GRN, 2005). In 2012, it became mandatory for any project in the natural environment, including all woody biomass harvest operations (≥ 150 ha), to develop comprehensive environmental management plans and acquire clearance from the Namibian government's environmental commissioner (MAWF, 2017). For large scale bush control operations > 5000 ha, clearance is provided, based on a full environmental impact assessment.

All harvest projects are expected to develop a general environmental management plan in accordance with the template developed by the Namibian Agriculture, Water and Forestry ministry. This addresses several potential impacts that must be managed. All projects should avoid (a) damage to protected and large trees, and to rangelands, (b) disturbance to wildlife and livestock, soil erosion and loss of soil fertility, (c) pollution of water sources and air, (d) regrowth, and (e) maintain the health and safety of workers. The general management plan can be modified to accommodate new actions and impacts that are relevant to any woody biomass harvest operation (MAWF, 2017).

In 2022, the Namibia's Ministry of Environment, Forestry and Tourism (MEFT) launched a 5 year (2022–2027) national strategy on the sustainable management of bush resources.

This strategy was developed with the involvement of different stakeholders in government, the private sector and civil organisations to guide bush biomass utilisation for long-term sustainability (MEFT, 2022). The strategy is based on several key principles aimed to promote environmental, ecological and sociological sustainable practices in biomass management. This strategy has principles that provide for the adequate protection and maintenance of biodiversity, ecosystems, and essential ecological processes, monitoring and evaluation, sustainable development and economic growth, resilience, adaptation to climate change, and the promotion of a low-carbon development pathway. Moreover, the strategy identified key priority areas and knowledge gaps, such as the contribution to enhanced biodiversity, research and development.

1.3 Potential impacts associated with bush encroachment control from physical tree/shrub removal

Thinning is widely applied as a forestry management strategy to achieve ecological and commercial objectives. This includes the selective reduction of woody plant biomass to minimise competition, fire risks and insect infestations, promote species richness and diversity, understory herbaceous cover, underground water yields, soil moisture conditions, as well as accelerate timber growth and yields (Birch and Middleton, 2017; Brown et al., 2019; Groengroeft et al., 2018; Haussmann et al., 2016; Honsbein et al., 2017a; MITSMED, 2017; Richter et al., 2001; Ritchie and Skinner, 2014; SAIEA, 2016; Smit, 2001, 2014; Stafford et al., 2017; West, 2014). Also, restoration of the encroached habitat would be beneficial for the cheetah, a large predator and fastest land mammal, known to rely on long sighting lines and grass cover for concealment while hunting (Marker et al., 2018a). A significant cheetah population (~1500 adults and adolescents) resides in Namibia, of which the majority (> 80%) occur on freehold farmlands (Marker et al., 2018b). Cheetahs are threatened by habitat loss, habitat fragmentation and human-predator conflict and continue to undergo population decline and reduction in range (Jeo et al., 2018).

Modification of the dense to sparse vegetation structure may not be appropriate for all wildlife due to differences in habitat requirements and feeding habits. For example, while grazing ungulates would benefit from increased grazing capacity, browsers would be negatively affected due to the decline in their food source. Namibian cheetahs are known to prefer certain browsing prey species (e.g. kudu *Tragelaphus strepsiceros*, duiker *Sylvicapra grimmia* and steenbok *Raphicerus campestris*) (Marker et al., 2018c, 2003). Thus, a decline in the browsing capacity due to the physical removal of trees/shrubs has the potential to negatively impact on these prey species, which could result in their decline, change in activity patterns, as well as local distribution. Lack of prey or low abundances are some of the factors known to promote human-predator conflict as cheetahs may then prey on unprotected livestock (Dickman et al., 2018; Marker et al., 2018c).

Woody plants also exhibit varied responses in relation to thinning: higher thinning intensity causes significant reduction in woody plant density, which results in greater growth rates amongst the retained plants as competition is reduced (Smit, 2014). Also, reproductive output, sapling establishment and survival increase with the reduction in woody plant density and canopy cover (Brown et al., 2019; Dwyer and Mason, 2018; Smit, 2014). Eventually, in the absence of appropriate post-thinning management, these conditions could promote further encroachment, which could mean that restoration efforts only have short-term success (Eldridge and Ding, 2021).

Bush thinning may impact on the carbon stocks and carbon sequestration potential of the savanna ecosystems, which exacerbates climate change, as adequate woody vegetation cover is required for the carbon sink function. For example, a previous study in the north-central farmlands of Namibia (Musekiwa et al., 2022) has shown that bush-encroached areas had greater soil organic carbon and total carbon stocks, and sequestered more carbon than areas where manual and chemical bush control had been applied. It is possible that the period of that study was not sufficiently long for carbon stocks to recover, especially since encroaching native species are known to experience slow growth rates, high mortality rates and limited recruitment, and a longer study period may be required to fully understand the effects of thinning on carbon dynamics (Cunningham and Detering, 2017; Joubert et al., 2017, 2013)

The option of no bush control would address the objective of carbon capture and carbon storage, but not habitat restoration and sustainable biomass utilisation. Such an objective may be difficult to implement without significant investments or incentives, especially because of the immediate economic losses experienced by livestock farmers if the status quo (i.e. no bush control) is maintained. Over time, older bush-encroached areas with greater carbon stocks may become vulnerable to intense veld fires due to the accumulation of deadwood and could potentially increase CO_2 emissions to the atmosphere. Thinning, if implemented within acceptable levels, is promising since it allows natural regeneration to occur and consequently, over the long-term, this increases the potential for carbon sequestration and the development of desired vegetation structure (Dwyer et al., 2010; Dwyer and Mason, 2018; Smit, 2001). Bush thinning is advantageous since it promotes sustainable biomass utilisation and restores rangeland productivity and wildlife habitats for open savanna adapted species.

A study by Zimmermann et al., (2017) has shown that bioassay experiments from soils in bush-encroached areas had greater growth rates than areas where complete tree/shrub clearing had taken place. This would suggest that tree/shrub removal could result in the net loss of soil nutrients and reduced soil fertility. Loss of soil fertility by any means is a concern in that it threatens land productivity and livelihoods, specifically in the inherently poor nutrient content Namibian soils.

1.4 Research framework for the thesis

1.4.1 Environmental management framework

This thesis is based on studies carried out to investigate the response of local wildlife, vegetation and soils to treatment (no thinning, thinning). Bush control by means of tree/shrub thinning is a targeted anthropogenic intervention aimed to restore encroached savanna habitat to its former natural state. Thus, this thesis centres on the theory of environmental management and its related principles to understand the underlying mechanisms pertaining to bush encroachment and its control (Figure 1).

Environmental management is a governance strategy that is aimed at protecting the earth's resources by regulating human impacts including production, consumption and activities or products; and the protection of biodiversity and the abiotic components of ecosystems (e.g. soils, air, and water) (Ruppel-Schlichting, 2016b). It is expected that by protecting the environment, higher standards of safety, security and benefits could be achieved. As an example, tackling global warming as the cause of environmental disasters would benefit the safety and security of the global community. Correspondingly, the protection of ecosystems from pollution and unregulated human-nature interactions would

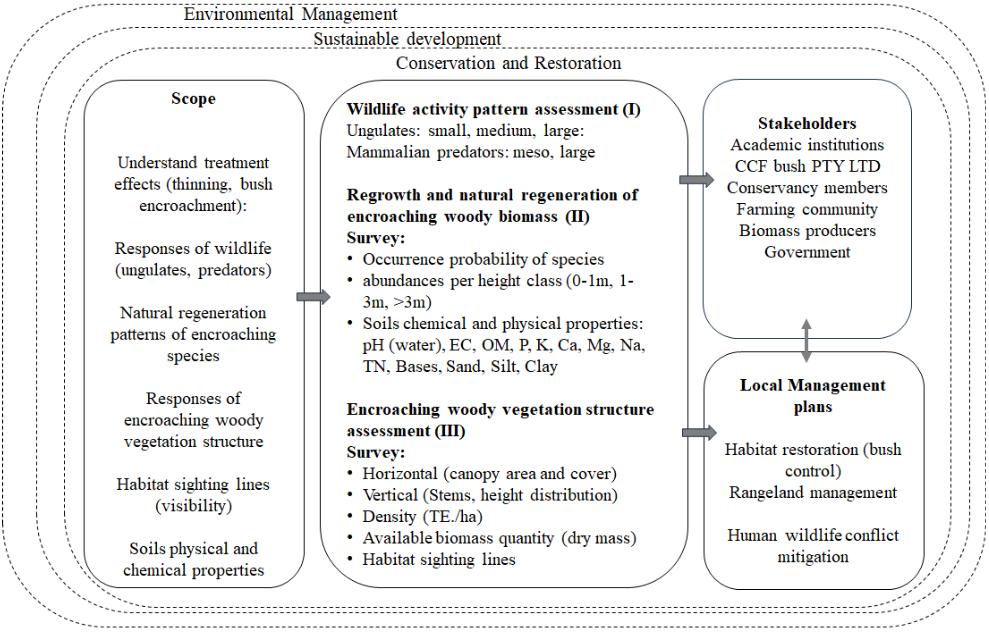

Figure 1. General framework for the thesis

bring numerous benefits, such as enhanced air and water quality, assured biodiversity, improved livelihoods, and minimised species extinctions due to human causes. Further, it would lead to a reduction in environmental costs by improving environmental performance and minimise environmental risks. An environmental performance is a measure used to evaluate whether the management goals of environmental health and sustainability amongst entities and states are being attained. Such measures are necessary and can be used as policy tools to monitor the progress made in achieving the goals of environmental health and sustainability (Ruppel-Schlichting, 2016b).

Environmental management derives its authority from well-established legal frameworks. Globally, this is contained in the United Nations (UN) Stockholm (1972) and Rio de Janeiro (1992) declarations that contain specific principles committed to guiding the process of environmental management and governance (UNCED, 1992; UNEP, 1972). The UN principles relevant to this thesis include (a) sustainable development, and (b) conservation and restoration of the health and integrity of the earth's ecosystems.

a) Sustainable development

Sustainable development (SD) is an organising principle used to advance human development goals by ensuring that the needs of present generations are met without compromising the ability of future generations to satisfy their own needs (WCED, 1987). It recognises the interdependence of humans on natural systems for vital ecological services and resources. Environmental protection is vital to ensure ecological integrity and productivity for long-term human safety and security. It is assumed that a balance can be reached in which the needs of present human generations are met without significant negative effects on the environment. Consequentially, this would lead to inter-generational equity where future generations would be able to meet their needs from the same environments. The SD principle is organised according to three interacting dimensions whose balance is important to achieve sustainability: Social, economic and environment (Mensah, 2019; UN, 2022).

The social dimension deals with improving the quality of life and the overall wellbeing of people. This is achieved through the eradication of poverty and hunger, inclusive and equitable quality education, promotion of lifelong learning opportunities, gender equality and female empowerment, decent employment, reduced inequalities, sustainable cities and communities, peace, justice, strong institutions, as well as good health and wellbeing (UN, 2015). Moreover, the social dimension also deals with the promotion of ethics, culture, community development and environmental law. The economic dimension deals with economic development and the improvement of living standards. Considerations include, amongst others, poverty eradication, sustained economic growth, decent employment for all, inclusive and sustainable industrialisation, innovation, construction of resilient infrastructure, responsible production methods and consumption (UN, 2015). This dimension aims to address economic growth and prosperity compatible with society and the environment. The environment dimension deals with the responsibility to safeguard biodiversity and its abiotic components through conservation, resource management, environmental protection, restoration and preservation. Other aspects addressed include the sustainable management of water and sanitation for all, access to affordable, reliable sustainable and modern energy for all, sustainable consumption and production patterns, combating climate change, promotion of the protection, restoration and sustainable use of terrestrial and marine ecosystems, forest management, as well as the halt and reverse of land degradation and biodiversity loss (UN, 2015). Implementation of these practices is vital to reduce stressors and risks to species and ecosystems (e.g. pollution, extinction, or exploitation of resource) and to promote environmental health, which is vital for human wellbeing.

b) Conservation and restoration of the health and integrity of the earth's ecosystems

Conservation of biodiversity and the environment, as well as the restoration of the health and integrity of the earth's ecosystems, have been identified as urgent goals to achieve sustainable development (UN, 2015). Global human populations are on the increase, placing more pressure on natural resources to provide various ecological services, food, medicine and materials. Hence, sustainable utilisation is an important aspect for conservation to safeguard biodiversity and ecosystems from destruction and to ensure inter-generational equity.

Conservation deals with the sustainable use and management of biological and non-biological resources, while ecological restoration is a conservation management strategy aimed at the initiation or acceleration of ecosystem recovery along a historic trajectory following damage, degradation or destruction (MacMahon, 1997). Thus, with ecological restoration, practitioners initiate the favourable conditions needed for recovery, and allow biodiversity to stabilise the ecosystem through natural regeneration and succession. In general, good conservation management is based on four basic principles: i) maintenance of critical ecological processes and biodiversity; ii) minimising of external threats and maximising external benefits; iii) conservation of evolutionary processes, and iv) adaptive management (Ronald Carrol and Meffe, 1997). These principles are hereafter discussed and linked to this study.

i) Maintenance of critical ecological processes and biodiversity

This principle states that conservation management should look beyond a species-by-species approach and place emphasis on the maintenance of ecological processes and biodiversity composition. A species-by-species approach is limited and does not consider the complexities in a particular area, such as species interactions or the processes necessary to maintain habitat and population structure. Hence, there is a need to focus on the protection of all other species, their habitats, as well as the processes that are important for the maintenance of ecological structure. Also, management plans cannot be developed for every single species present in the ecosystem, hence the need for a wider management approach. Umbrella species and ecosystem protection are used as strategies for wider conservation. In the umbrella species approach, conservation is focused on charismatic or threatened species, as well as their habitat and resources. Consequentially, this has multiple benefits since protection is extended towards other species and habitat features that are often overlooked. Similarly, an ecosystem approach can provide protection to all species and vital ecological processes.

In Namibia, charismatic predators, such as the cheetah, are ideal candidates for the umbrella and keystone species approach due to their long ranging behaviour that extends over large territories (mean area = 1651 km^2) (Marker et al., 2008). Securing cheetah populations over larger landscapes could extend greater benefits to the ecosystem, especially since other native species (including prey) and their habitat are protected. However, without appropriate human wildlife mitigation strategies, such as guard dogs to reduce livestock predation risks (Dickman et al., 2018) and habitat restoration by bush control and alternative livelihoods (Wykstra et al., 2018), the sustainability of implementing this approach in the current cheetah ranges would be under threat.

ii) Minimising external threats, and maximising external benefits

This principle states that conservation areas could experience effects (negative, positive) from the surrounding community. Thus, it is important to focus on three fundamental questions: (a) in what ways can conservation areas be protected from external effects (e.g. poaching, pollution)? (b) In what ways can neighbouring communities provide potential benefits to the area? (c) In what ways can communities participate in the decision-making process related to the conservation area (Ronald Carrol and Meffe, 1997)? Inclusion of local people in conservation is important to safeguard biodiversity outside the protected areas. This is because protected areas cannot be viewed as islands on their own but are part of a wider landscape that is interconnected with people and their livelihoods, which could potentially influence the success of conservation (Powell et al., 2018). One strategy to minimise external threats is the development of buffer zones around conservation areas (e.g. conservancies), which allow economic activities be carried out by the surrounding communities.

In Namibia, approximately 86% of the territory falls outside of the state-run protected area network, where livestock farming is the most dominant land use type (Kauffman et al., 2007). This unprotected area matrix is important for biodiversity conservation, specifically since it supports livestock farming, is a refuge to wildlife, and is home to a significant global free-ranging cheetah population (~90%) (Marker et al., 2018b). This exposes these wildlife species to vulnerabilities including human-wildlife conflict, poaching, loss of suitable habitats from land degradation (e.g. bush encroachment), habitat fragmentation, population decline and accelerated loss of genetic diversity (Jeo et al., 2018; Verschueren et al., 2020). Therefore, the establishment of buffer zones, in the form of larger landscapes, such as proposed by the conservancy model, are important for good conservation management. Conservancies are self-selecting social units comprised of communities of people that choose to work together. They are joint land tenure agreements that give greater rights and flexibility in management to local communities who agree to manage their lands based on stewardship under ecological principles (Powell et al., 2018). This strategy is beneficial towards biodiversity in that it (a) creates a safety zone around the protected area, (b) increases the total land surface area under protection, and (c) provides habitat corridors for the dispersal of migratory species within the landscape. Protected areas alone are not adequate, especially for large wide-ranging migratory mammals, hence there is a need for large landscape-level conservation (Jeo et al., 2018). Also, provision of connectivity between conservation areas and other ecosystems would facilitate dispersal and gene flow, and would minimise over-utilisation of protected areas by wildlife.

iii) Conservation of evolutionary processes

This principle states that species should not be conserved as if they were static, but as participants in an evolutionary process. For good conservation management, it is imperative to consider that the maintenance of large population sizes for species would guard against stochastic extinctions and would ensure sufficient genetic diversity, which can allow species to adapt to changing environmental conditions. Small populations are more vulnerable to stochastic environmental events, which accelerate extinctions. Hence, the maintenance of favourable ecological conditions (e.g. via bush control) could be beneficial to ensure stable population sizes at reasonable levels, which would also favour genetic diversity (Jeo et al., 2018).

In this thesis, investigations were carried out to determine the effects of treatment (thinning, no thinning) on wildlife, vegetation structure, soils, and habitat sighting (see articles **I**–**III**). It is expected that by restoring open savannah structure, rangeland productivity would be increased. Consequentially, this could boost prey populations, prevent the rapid decline in cheetah populations and slow the loss of genetic diversity (Marker et al., 2018c).

iv) Adaptive management

To meet new contingencies, management should be flexible because of changes in environmental conditions and the new challenges that may arise. Also, it is imperative to have contingency plans that can be implemented in the event that the original plans fail. Adaptive management is an iterative process that involves learning by doing (management) and adjusting management activities to reflect new information as our understanding improves (Williams and Brown, 2016). Hence, it relies on system monitoring using specific targets selected by management; for example, whether certain goals have been achieved, by using specific indicators (e.g. social, economic, and environmental) to provide feedback mechanisms for decision-making. Over time, this process would improve long-term management outcomes and reduce uncertainty as robust decisions are made based on existing evidence.

Despite these benefits, practitioners face some challenges in the implementation of adaptive management. These include identification of the objectives, and ensuring stakeholder agreement on what should be monitored, since they may assign different importance to system attributes (Williams and Brown, 2016). Also, systems monitoring could face other challenges that include dealing with multiple uncertainties that could make decision-making and monitoring complex, the long-term commitment to monitoring, as well as the allocation of funding. In this thesis, the results from articles **I**–**III** will increase our understanding of the effects of bush encroachment and its control. Thus, the results can be used to alter or prevent management decisions and activities for bush control.

1.4.2 Ecological disturbance theory

The ecological disturbance theory is used as an exterior scope to focus on what may happen to the natural system from the implementation of environmental management. This theory posits that a disturbance is a discrete event that arises from the natural or anthropogenic causes experienced by an ecological component or system. Such events have potential to cause significant alterations in the environmental conditions, such as biomass availability, ecological structure and its functions (Archer et al., 2017; Burton et al., 2020). Savannah ecosystems are known to have co-evolved with natural disturbances, especially occasional fires, and from migratory herbivores (Archer et al., 2017). These disturbances have maintained open vegetation structure by reducing tree/shrub densities, canopy cover and biomass accumulation. It is widely understood that anthropogenic influences have led to the alteration of these key ecological disturbance regimes, thereby resulting in the proliferation of a dense vegetation structure with little grass cover and limited sighting lines (see section 1.1). Bush control by thinning trees/shrubs is relevant to this theory because it is a type of anthropogenic disturbance that involves the physical removal of trees/shrubs to reduce excess woody biomass, increase grazing capacity and wildlife habitat. However, this may alter the tree/shrub population structure, soil nutrients, carbon stocks (above- and below-ground) and wildlife habitats. Increasing the amount of tree/shrub removal beyond the ecosystem threshold could cause significant negative responses amongst the local biotic and abiotic components of the environment (see section 1.3).

The level (i.e. size, intensity, and frequency of occurrence) of disturbance determines the different effects that can be beneficial or detrimental towards species and ecosystems. For example, with regard to community structure, the intermediate disturbance hypothesis (IDH) suggests that disturbances that are neither too rare nor frequent nor intense would maximise species richness and diversity at the local level (Connell, 1978). Greater species richness and diversity levels is assumed because disturbances reduce species densities, which eventually decrease competition for resources as population abundances are temporarily reduced but recover at a later stage. Moreover, it is also assumed that such events also prevent and interrupt competition exclusion and the attainment of ecological equilibrium. Thus, coexistence amongst species with different competitive abilities (weak and strong) and tolerance levels towards disturbances (sensitive, tolerant) is attained. This level also allows more time for species to recover, especially those with slow growth rates (k-selected species) or poor ability to disperse rapidly. This hypothesis also predicts that species richness and diversity are expected to be low when levels of disturbance are either low or high. At the low-level of disturbance, it is predicted that competitive superior species would exclude other weaker species that typically thrive in disturbed habitats and have greater intrinsic rates of growth (e.g. r-selected species). Thus, low-disturbed ecosystems tend to be dominated by disturbance-sensitive species (e.g. k-selected) that tend to have slow growth and reproductive rates, but exhibit greater competitive advantage for resources. At high-levels of disturbance, more perturbations are expected and may exceed the tolerance levels of sensitive species, which could lead to increased mortality and local extinctions. Also, highly-disturbed areas would attract pioneer species with greater intrinsic rates of growth and short generation times, for example unpalatable annual grasses that could lead to poor grazing capacity.

1.4.3 Environmental management aspects related to bush encroachment control in Namibia

The Namibian constitution, adopted at independence in 1990, contains specific clauses that provide for the achievement of sustainable development. Specifically, Article 95 (1) commits the state to ‘actively promote and maintain the welfare of people by adopting policies aimed at the maintenance of ecosystems, essential ecological processes and biological diversity, and utilisation of living natural resources on a sustainable basis’ (GRN, 1998). Moreover, Article 90 (c) assigns responsibility to the Ombudsman to ‘investigate complaints concerning the over-utilisation of living natural resources, the irrational exploitation of non-renewable resources, the degradation and destruction of ecosystems and failure to protect the beauty and character of Namibia’. These constitutional provisions compel the state to incorporate sustainable development as a key principle in national development policies.

To achieve sustainable development, the Environmental Management Act (EMA) (No.7 of 2007) was published and came into force in 2012 (Ruppel-Schlichting, 2016b). This act functions as framework legislation for development activities prior to their commencement, in order to prevent irreversible damage to the natural environment. Further, it aims to promote the principles of sustainable development by safeguarding natural resource availability and benefits for both present and future generations. It ensures that impact assessments are conducted in a timely manner prior to development, mitigation strategies are identified, stakeholder participation is recognised, and resource users are held accountable for any environmental damage they may cause. This act is relevant for bush encroachment control, since uncontrolled or injudicious removal of native woody biomass from the savannah landscape could negatively affect habitats in terms of biodiversity, and essential ecosystem services, such as water, soil nutrients and grazing, which are essential resources for agricultural productivity.

Despite these regulatory frameworks, there are concerns with regard to uncontrolled harvesting especially of mature trees/shrubs (stem diameters $\geq$ 18 cm diameter), protected species, and overharvesting of woody biomass for its economic benefit (MAWF, 2017). Also, due to the vastness of the bush-encroached landscape and limited capacity, there are challenges with regard to the enforcement of policy conditions related to the achievement of environmental sustainability, since foresters and environmental inspectors are not able to conduct timely field inspections. Best practices in the biomass industry could be enhanced by certification of timber and non-timber products from areas that are managed, with a strong focus on the promotion of biodiversity conservation and ecological processes, as well as social responsibility (e.g. Forest Stewardship Council (FSC) certification). Through periodic audits and surveillance, certification could ensure that biomass producers adhere to standards that promote environmental compliance and social responsibility in accordance with local and international laws and policies (FSC, 2019).

1.4.4 Previous knowledge on the effects of vegetation removal relevant to this thesis

Bush encroachment has been investigated in a broad variety of settings across southern Africa, although the effects on biodiversity remain largely unknown (Soto-Shoender et al., 2018). Most of the available knowledge has focused on the effects of mechanical clearing, chemical control or prescribed fire, which are generally nonselective, with limited focus on restoration thinning. Studies on wildlife responses (Isaacs et al., 2013; Schwarz et al., 2018) have focused primarily on herbivore preferences to the exclusion of predators. Also, studies that have investigated the effects on soils (Buyer et al., 2016; Zimmermann et al., 2017) have excluded aspects of the physical and chemical compositions. A few studies (Harmse et al., 2016; SAIEA, 2016; Smit, 2001) have described the specific responses of thornbush species and vegetation structure modifications. This indicates a lack of knowledge with regard to a much deeper understanding of the regeneration of encroaching trees/shrubs and the success of bush control interventions. This thesis aimed to contribute to existing knowledge by providing a better understanding of the effects of treatment (non-thinned, thinned) on local flora, fauna and soils on farmlands with integrated livestock and wildlife management regimes. Further, the thesis sought to provide baseline data and indicators that could be used to evaluate the efficacy of restoration thinning and to identify appropriate management actions in similar affected areas. Also, research of this nature would contribute to the knowledge gap that has been identified within Namibian national priority areas with regard to woody biomass harvesting and utilisation for the period 2022–2027 (MEFT, 2022).

1.5 Aims and hypotheses of the thesis

The thesis aimed to assess the effect of restoration thinning on native wildlife and encroaching woody vegetation in relation to baseline conditions (non-thinned areas), to identify responses and demonstrate the effectiveness of this method (thinning) in reducing bush encroachment in north-central Namibia.

Specific aims were to examine:

I. The response of local ungulates (small, medium large) and predators (meso, large) to the thinning treatment (Article **I**).
II. The response (regeneration) of encroaching species to the thinning treatment (Article **II**).
III. The effects of treatment (thinned vs non-thinned) on the vegetation structure (abundance, biomass, canopy cover) and habitat sighting lines (Article **III**).

Hypotheses:

I. Thinning would significantly increase the activity of small, medium and large ungulates, meso and large predators, and that there would be significant interactions between treatment (thinned, non-thinned) and animal types (Article **I**).
II. Thinning would not disturb soil properties, and that thinning would reduce the abundance of encroaching vegetation species (Article **II**).
III. Thinning would reduce the abundance of encroaching vegetation species, the magnitude of the impacts at thinned sites would differ between tree/shrub types, and thinning would significantly modify the vegetation structure and restore sighting lines for improved detection (Article **III**).

Plausible explanations for the hypotheses:

Article I: A higher wildlife activity (Article I) is predicted in thinned areas due to its ideal habitat structure for open savannah adapted species. It is expected that thinned areas would have greater: a) grazing capacity that would attract prey species, b) grass cover utilised by predators for concealment while hunting, c) habitat sighting lines relied upon for detecting distant predators or prey, and d) reduced tree/shrub densities that allow ease to manoeuvre through the habitat with less energy expenditure (see sections 1.1 – 1.3).

Article II: A minimal or no effect on the soil properties is predicted, since a selective thinning method was applied during the harvesting process that causes minimal disturbance to the soil and harm to biodiversity (see section 1.2). During the harvesting process, some trees/shrubs were retained to provide habitat for wildlife allow the continuation of nutrient cycling.

Articles II-III: A reduction of the abundances of encroaching species is predicted, since thinning woody densities would result in the physical removal of trees/shrubs, causing direct mortality, and the contraction of the population size. Also, all harvested trees/shrubs are treated with an arboricide to suppress coppicing and rapid re-encroachment. The magnitude of the impacts at thinned sites is predicted to differ between tree/shrub types (Article III) due to the local variation in environmental conditions which could also influence the densities and distribution of encroaching in the study area. The magnitude of the impacts amongst species would also differ since species may exhibit different responses due to differences in their reproductive output, survival, and resilience to disturbances. Impacts may also differ due to harvester preferences for certain species. Longer sighting lines (Article **III**) are expected as the tree/shrub densities, biomass and canopy cover are reduced.

The research scheme presented in this thesis is based on the scope definition, research inputs and the research process, which are presented in three articles and a summary linked to the ongoing scientific discussion in the field (Figure 2). In Article **I**, the results of a wildlife camera trap survey of three ungulate (small, medium, large) and two predators (meso, large) in thinned and non-thinned habitats are presented. The results show the response in wildlife activity patterns in relation to treatment (thinned vs non-thinned), the animal type that was most responsive to the treatment, and the influence of independent variables on photographic captures. In Article **II**, the results of a vegetation survey of five woody species known to cause encroachment are presented. The results show the effects of treatment on the occurrence probability of trees/shrubs, regeneration of encroaching species following thinning, the species that were most responsive to thinning, and the influence of covariates, which included post-thinning age and arboricide aftercare application. In addition, the results of a soil survey are presented that identified differences in physical and chemical properties between treatments. In Article **III**, the results of a vegetation survey of five woody species known to cause encroachment are presented. The results show the effects of treatment on vegetation structure (density, canopy area, tree/shrub size, dry biomass) and the influence of covariates, which included post-thinning age and arboricide aftercare application. In addition, the results of habitat sighting lines (to characterise habitat suitability for predators (e.g. cheetah) that rely on long sighting when hunting) is presented to show how sighting visibility compares between treatments.

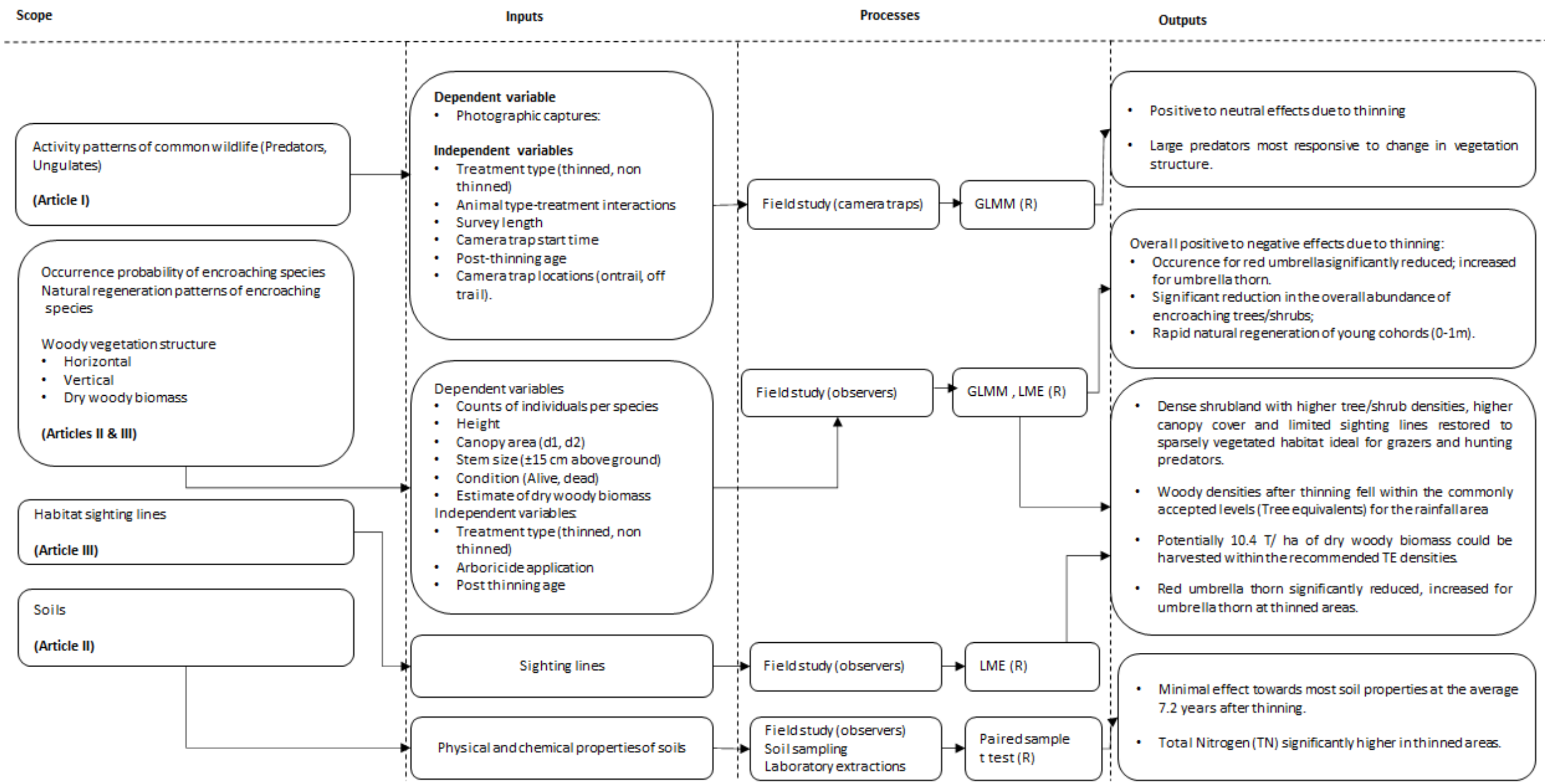

Figure 2. Schematic representation of the research conducted and outline of Articles **I-III**.

2 MATERIALS AND METHODS

2.1 Study area

This doctoral study was conducted on three freehold farms of approximately 174.2 km^2; Cheetah View (#317), Boskop (#324) and Elandsvreugde (#367), located in north-central Namibia (-20.477299 S, 17.024623 E; 1580 m above sea level; Figure 3). These farms were primarily used for livestock and wildlife ranching and contain semi-permanent water resources (earth dams and troughs) to provide year-round drinking water. The farms were fenced (1.5 m high cattle proof) with interiors subdivided into multiple large camps to restrict livestock to grazing camps but that allowed free movement of wildlife. The climate is semi-arid, with three distinct seasons: hot and dry (September–December), hot and wet (January–April), and cold and dry (May–August). Mean (± sd) annual rainfall is 444 mm (± 17.1) but was 401 mm (± 257.4) between 2002–2012. Mean annual temperature is 19.2°C (± 2.4) with mean daily maxima of 22.7°C (±0.7) in January and 13.4°C (±0.7) in July (Fick and Hijmans, 2017). The vegetation is described as thornbush shrubland with dominant woody plant genera, which consist of *Dichrostachys, Senegalia, Vachellia, Terminalia, Combretum* and *Grewia* (Curtis and Mannheimer, 2005; Mendelsohn et al., 2003). The vegetation structure is dense thornbush, and as a consequence, grazing carrying capacity and habitat sighting lines are poor. The soils are described as Eutric Regosols and Chromic Cambisols, with sandy loam and loamy sand common (Mendelsohn et al., 2003; Zimmermann et al., 2017). Since 2005, bush thinning operations have been conducted on all three farms under the Forest Stewardship Council certification for sustainable forestry (certificate: FSC-C004580).

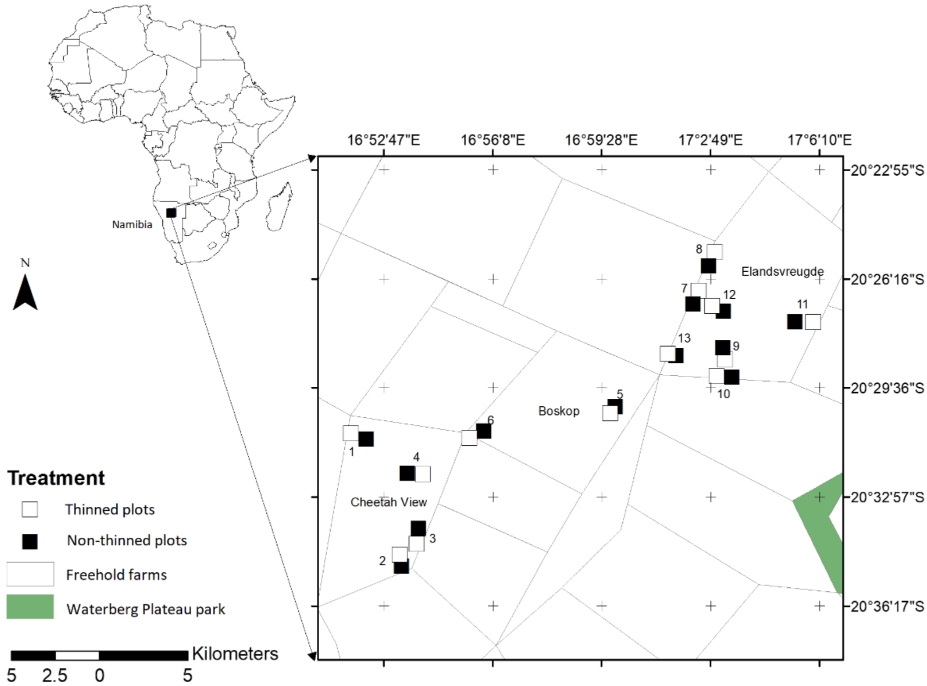

Figure 3. Study area showing the location of the surveyed farms in north-central Namibia. White and black squares represent blocks (plot pairs). Open squares represent thinned plots and black squares represent non-thinned plots.

2.2 Experimental design

The research in this thesis utilised a combination of blocked and split-plot design that consisted of a previously thinned and a non-thinned plot located in proximity (Figure 3, Figure 4, Figure 5). This involved a total of 13 blocks (plot pairs) each with a paired thinned and non-thinned plot, which were equally matched geometrically (26 plots: 13 non-thinned, 13 thinned). The non-thinned bush-encroached area served as the control treatment, and the plots were placed within ~700 m of the thinning treatment with a similar vegetation and management history (Figure 3, Figure 4, Figure 5). The thinning plots were in areas that had been manually harvested with hand-tools (axes, machetes) to control bush encroachment. These plots had been thinned manually at different time periods between 2002–2013, hence they differed in post-thinning age, size and location (Figure 3, Figure 4, Figure 5).

Investigations involved three large predators, four large ungulates, four meso predators, a medium ungulate, two small ungulates, and five woody plants known to cause bush encroachment in the area. Soil physical and chemical properties, and sighting lines of the areas were measured to characterise wildlife habitat suitability. These aspects were selected because i) they were directly affected by bush encroachment or thinning, and could be used as indicators for impacts, and ii) the wildlife and vegetation species have an economic value and are of conservation importance. As an example, all wildlife and woody species selected were utilised on a consumptive and non-consumptive basis; wildlife were assigned a conservation status from huntable to protected and tree/shrubs that were known to cause bush encroachment were selected. Sighting lines (detection range) of the areas were evaluated since they are typically associated with areas preferred by cheetahs (Muntifering et al., 2006; Nghikembua et al., 2016a).

Selection of plots was opportunistic since it followed areas targeted for bush thinning based on area accessibility and severity of bush encroachment prior to the conception of this study. Plots were also selected based on whether they met a minimum area size (plot width and length > 100 m) and whether thinning had taken place three years prior or more to this study to allow for the development of responses over multiple seasons. Tree/shrub densities had been thinned (~50%) during a single thinning cycle per plot, and some vegetation thickets were retained to provide browsing, shelter and habitats for biodiversity. To prevent regrowth from coppicing, aftercare was applied on freshly cut stumps with an arboricide, commercially known as Access® (Picloram and Triclopyr active). This was carried out on 11 plots that were thinned before 2005; two plots were not treated with Access®, hence aftercare treatment was considered as a covariate during the statistical modelling process. Harvested biomass were removed from the area for wood briquette production. Small branches, twigs and stumps were left in the field.

For the collection of data, multiple subplots were placed within each plot. Subplots were generated by overlaying a regular 100 m^2 grid over each plot for evenly spaced multiple points. A systematic random sampling approach was followed for the selection of subplots, which resulted in 52 camera trap locations, 295 circular subplots with a 6 m radius (113.1 m^2) for the collection of vegetation data, and 293 sighting lines, as well as 208 soil sampling points (8 per plot). The software program ArcGIS 9.3 (ESRI, 2008) was used for this task, and Hawths Sampling Tools were used for randomisations (Beyer, 2004). Geographic coordinates (Longitude, Latitude) were assigned to all subplots, and were uploaded on a handheld GPS unit (Garmin Etrex 30, Garmin international, Inc., Olathe, Kansas, USA) to track positions during surveys**.** At each plot, the location and boundaries were clearly marked with flagging tape.

Camera trap placements included randomised spots or suitable areas within a 50 m radius that incorporated game trails and off-trails to maximise detection probabilities of the different wildlife species (Cusack et al., 2015; Fabiano et al., 2018; Mann et al., 2015; Walker et al., 2016). All control and thinning treatment plots had an equal number of stations (52 total, 26 per treatment area) and balanced placements (off-trail: n=12 thinned, n=12 non-thinned; on-trail: n=14 thinned, n=14 non-thinned). Camera traps are triggered by moving objects, especially if detected at close range or if the camera is exposed to direct sunlight and high temperatures. To overcome these issues, grass and small bushes (≤ 1 m) within 5 m of the detection range were cleared to create a line of sight with no obstructions, and available shade spots were utilised for placement to avoid direct sun exposure. Prominent sun directions during the day were avoided to prevent direct sun exposure by orienting camera traps away from the northeast and southwest. To maximise animal captures, camera traps were oriented in the direction that the animals were likely to appear, and placed on tree trunks or metal poles at approximately 60 cm aboveground.

Wildlife surveys were carried out from September 2016–July 2017 over two rotations at the same location, mainly using the Bushnell® Trophy Cam camera trap model (91.4%) and Spypoint® BF10 HD cameras traps (8.65%). Camera trap sensitivity was set to low, thereby allowing a single shot to be taken at 10 sec intervals. Stations were active for a minimum of 21 days and a maximum of 36 days (Article **I**)

Soil surveys (Article **II**) were carried out from June to July 2016. Samples were collected to a depth of 20 cm, using a spade (at eight randomised locations per plot) and, thereafter, were stored in identifiable individual transparent plastic bags. All samples from the same plot were combined to form a composite sample and resulted in a total of 26 samples. Extractions were conducted by the Namibian Ministry of Agriculture, Water and Forestry (MAWF) Soil Laboratory using the Agri Laboratory Association of Southern Africa (AgriLASA, 2004) procedures. Soils were analysed for total nitrogen (TN), available phosphorus (P) and potassium (K), organic carbon (OC), sodium (Na), soil pH, available calcium (Ca) and magnesium (Mg), carbonate (CO_3^{2-}), electrical conductivity (EC), % organic matter content (OM) and identification of soil texture (sand, silt and clay fractions; sand and silt were determined by the pipette method).

Vegetation surveys (Articles **II** and **III**) were carried out from April to August 2017 by the principal investigator and two field assistants using direct observations. All target species per plot were quantified by individual counts, height, maximum canopy diameter from two perpendicular directions, stem diameter (15 cm aboveground) and condition (alive, dead). Height and diameters were measured using an extendable marked polyvinyl chloride (PVC) pipe (3 m length), a standard ruler (30 cm) and a measuring tape (30 m). Sighting lines were measured using a 1-m accuracy rangefinder (Bushnell Yardage Pro Scout 6×) in four random directions at each subplot separated by 90°. Sighting lines were measured by an observer at the centre of the subplot crouched at 0.65 cm height above-ground to simulate the average eye height of the cheetah.

Figure 4. Representation of non-thinned (left) and previously thinned (right) plots demonstrating the differences in vegetation structure. Non-thinned plots exhibit greater tree/shrub density, canopy cover, limited sighting lines and have less grass cover than thinned plots.

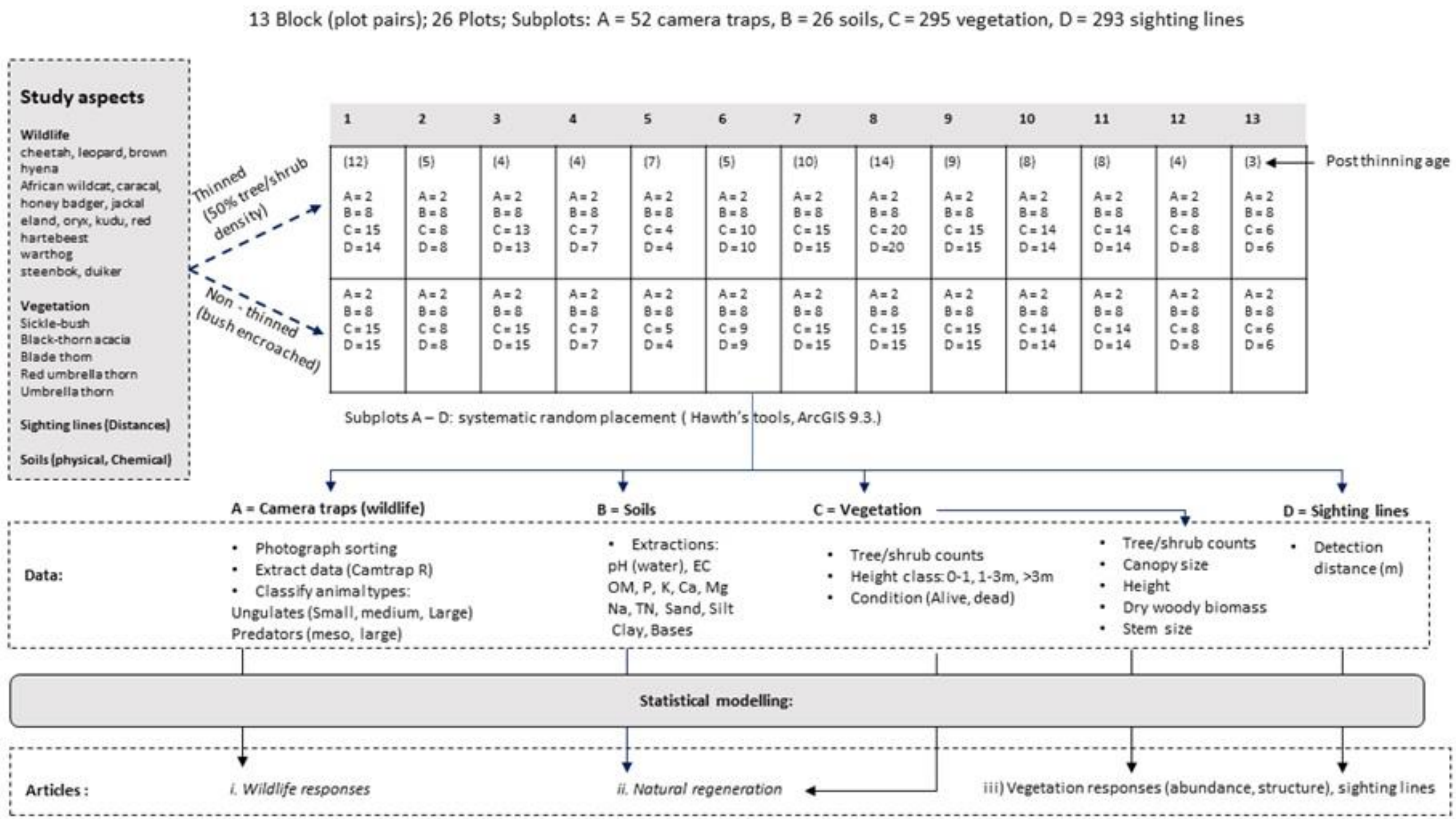

Figure 5. Layout of the experimental design in this thesis

2.3 Statistical analysis

The modelling tasks (Articles **I**–**III**) involved the use of a Generalised Linear Mixed-Effects model (GLMM) and a Linear Mixed-Effects model (LME) (Bates et al., 2015; Venables and Ripley, 2002). Hypothesis were tested at the $P \leq 0.05\%$ significance level. An observation level random effect (Articles **I-II**) was included following the detection of overdispersion, by exploring the ratio between the Pearson statistic P (sum of squared Pearson residuals) and the residuals degrees of freedom (n-p). A value > 1 indicated overdispersion (Mehtätalo and Lappi, 2020). The systematic part of all the final models (Articles **I**–**III**) was examined graphically by evaluating the trends and homoscedasticity of the Pearson and deviance residuals; normal q-q plots of random effects were used to evaluate the assumption of the normality of random effects (Mehtätalo and Lappi, 2020). Hypotheses testing for the GLMM model coefficients (Articles **I**–**III**) were based on Wald $\chi 2$ tests of the fitted final model using R functions Anova and lht of package car (Fox and Weisberg, 2011). All analyses were performed within R (version 3.5.2; R Core Team, 2017 and version 4.0.4, R Core Team, 2021).

*2.3.1 Response of wildlife to thinning (Article **I**)*

Wildlife photographs were identified manually to the species-level and all duplicate observations were deleted to obtain independent events. Extraction of image metadata (date, time, camera trap station, species) was achieved with the CamtrapR package (Niedballa et al., 2016). The response of wildlife to treatment types (thinned, non-thinned) was evaluated with a Poisson GLMM:

$$E(y_{kji}) = exp(\boldsymbol{x'}_{kji}\boldsymbol{\beta} + b_k + c_{kj} + d_{kji} + e_{kjih}) \tag{1}$$

where $E\ (y_{kji})$ is the mean number of image captures; $x'_{kji}\beta$ includes the effects of fixed factors; animal type, treatment, animal type-treatment interactions, camera trap start time (expressed as weeks since first camera was active in the study area), centred survey length (expressed as survey length - 21), centred post-harvest age (expressed as post-harvest ages minus 6.82, where 6.82 is the mean postharvest age over all treated plots) and camera trap locations (on-trail, off trail); $b_k + c_{kj} + d_{kji} + e_{kjih}$ includes the nested random effects for block (plot pair), plot, camera station, and observation respectively.

*2.3.2 Soil physical and chemical properties (Article **II**)*

A paired sample *t* test was used to compare mean differences in the soil properties between the thinned and non-thinned areas. The distributions of soil properties (EC, P, K, Ca, and Mg) were log-transformed to account for their larger standard deviations in comparison to the mean. This was carried out because the sample size was small, and the *t* test may be affected by skewness.

*2.3.3 Response of encroaching species to thinning (Articles **II** and **III**)*

Aftercare application with arboricide and post-thinning age were included as they may influence vegetation regeneration. Post-thinning age was expressed as time since thinning

minus 7.2 years, where 7.2 is the mean time since thinning over all treated plots. For the non-thinned treatment, the centred time since thinning was set to zero (0).
In Article **II**, a logistic GLMM via Penalized Quasi-Likelihood (glmmPQL) was used to estimate the probability of tree/shrub species presence in the thinned and non-thinned areas:

$$y_{kji} \sim \text{Bernoulli}\ (p_{kji}) \tag{2}$$

$$ln\left(\frac{Pkji}{1-Pkji}\right) = \boldsymbol{x'}_{kji}\boldsymbol{\beta} + b_k + c_{kj} + d_{kji} \tag{3}$$

where y_{kji} is the binary response (presence (1) or absence (0)) of tree/shrub species occurrence, p_{kji} is the probability of tree/shrub species occurrence; $\boldsymbol{x'}_{kji}\boldsymbol{\beta}$ includes the effects of fixed factors species, treatment, and the species-treatment interactions; $b_k+c_{kj}+d_{kji}$ includes the nested normally distributed random effects for plot-pair (block), plot and subplot, respectively.
To estimate the effect of treatment type on the vegetation structure and regeneration, counts of trees/shrubs from all five woody species were grouped according to three height classes: 0–1 m, 1–3 m, > 3 m. The modelling involved a Poisson GLMM formulated as:

$$E(y_{ki}) = exp(\boldsymbol{x'}_{ki}\boldsymbol{\beta} + b_k + e_{ki}) \tag{4}$$

where E (y_{ki}) = mean number of trees/shrubs; $\boldsymbol{x'}_{ki}\boldsymbol{\beta}$ includes the effects of fixed factors treatment, arboricide application and centred time since thinning; and $b_k + e_{ki}$ includes the nested random effects for block and observation, respectively. Plot and subplot were excluded in the final models due to close to zero variances in the random factor levels. In Article **III**, a GLMM via penalized quasi-likelihood (glmmPQL) was used to estimate how the woody species abundance and stem sizes (0–6 cm, 6–18 cm, >18 cm) were influenced by treatment:

$$E(y_{kji}) = exp(\boldsymbol{x'}_{kji}\boldsymbol{\beta} + b_k + c_{kj} + d_{kji}) \tag{5}$$

where E (y_{kji}) = mean number of tree/shrub counts; $\boldsymbol{x'}_{kji}\boldsymbol{\beta}$ includes the effects of fixed factors; tree/shrub species or stem classes, treatment, the tree/shrub species-treatment, or stem class-treatment interactions, arboricide application and post-thinning age; and $b_k + c_{kj} + d_{kji}$ includes the nested random effects for block (plot pair), plot and subplot, respectively. For the non-thinned treatment, the post-thinning age was set to zero (0).
The LME models were used to estimate the influence of treatment on the overall tree/shrub density (TE), canopy size, woody biomass availability and sightlines in four separate models of the form:

$$y_{kji} = \boldsymbol{x'}_{kji}\boldsymbol{\beta} + b_k + c_{kj} + e_{kji} \tag{6}$$

where y_{kji} = mean number of trees/shrubs (TE), canopy size, woody biomass, and sighting lines; $\boldsymbol{x'}_{kji}\boldsymbol{\beta}$ includes the effects of treatment, post-thinning age and arboricide aftercare as fixed factors; and $b_k + c_{kj}$ includes the nested random effects for block (plot pair) and plot, with e_{kji} the subplot-level residual error, respectively. Further, the LME model was also used to estimate how the vertical structure (height) of the areas was affected by the treatment:

$$y_{kjil} = \boldsymbol{x'}_{kjil}\boldsymbol{\beta} + b_k + c_{kj} + d_{kji} + e_{kjil}, \tag{7}$$

where y_{kjil} = mean tree/shrub height of the subplot; $\boldsymbol{x}'_{kjil}\boldsymbol{\beta}$ includes the effects of fixed factors; treatment, post-thinning age and aftercare application, and $b_k + c_{kj} + d_{kji}$ includes the nested random effects for block (plot pair), plot and subplot, with e_{kjil} the tree-level residual error, respectively. For all LME models, the non-constant residual variance was modelled by applying weighting (variance Power) following inspection of the residuals in the initially fitted models:

$$var(\epsilon_{kji}) = \sigma^2 |y_{kji}|^{2\delta}, \tag{8}$$

for tree/shrub densities (TE), canopy area, woody biomass, and sightlines and

$$var(\epsilon_{kjil}) = \sigma^2 |y_{kjil}|^{2\delta}), \tag{9}$$

for vertical structure (height),

where y_{kji} and y_{kjil} indicates group-level predictions for the models. Conditional F-tests on the fixed effects were carried out to determine significant predictors.

3 RESULTS

3.1 Response of wildlife to thinning (Article I)

Thinned areas had the most wildlife captures, and species-treatment interactions were close to significant (p=0.051). Overall, the predicted number of ungulates (small, medium, large) were the highest and predators (meso, large) were the lowest in both treatments (Fig 3; Article **I**, Tables 3 & 4). In the non-thinned treatment, the mean number of large predators was only 25% of the predicted amount in the thinned treatment (Article **I**, Tables 3 & 4). For the other animal types, less animals were recorded in the non-thinned treatment: 80.2% of the numbers in the thinned area for large ungulates, 58.5% for medium ungulates, 71.4% for meso predators and 98.5% for small ungulates.

Mean captures differed significantly between animal types. Large predator captures also differed significantly between treatments (Article **I**, Table 5). Other animal types were also positively influenced by thinning, although the differences between treatments were not statistically significant.

The numbers of animal captures were significantly positively related to camera trap start time (Article **I**, Table 5). Increasing survey length beyond 21 days by a unit (1 day) had a significant positive effect on the number of predicted animal captures (Article **I**, Table 5). Thus, captures increased by approximately 5.8% for every unit (1 day) beyond 21 days (Article **I**, Figure 4. Post-harvest age and camera placement did not have any significant effect on mean captures.

3.2 Soil physical and chemical properties (Article II)

The mean TN content differed significantly between treatments. The mean TN in the thinned areas was 21.8% (±38.1 sd.) higher than the mean amounts measured in the non-thinned area.

3.3 Number of observed individuals and species-treatment interactions (Article II and III)

The non-thinned area had the greatest overall expected abundance of trees/shrubs (non-thinned = 1136 ind. ha^{-1}, thinned = 523 ind. ha^{-1}). Differences between treatments in occurrence probabilities, and mean tree/shrub counts per species were statistically significant (Article **II**, Table 4; Article **III**, Tables 2–4). Across all species, sickle-bush had the greatest expected occurrence probability and abundance, followed by black-thorn acacia, with umbrella thorn the lowest in both treatments. The effect of the thinning treatment resulted in a significant reduction in the occurrence probability and abundance of red umbrella-thorn and a significant increase for umbrella thorn (Article **II**, Table 4; Article **III**, Tables 2–4). For other species, occurrence probabilities were reduced by thinning, although the differences were not statistically significant (Article **II**, Tables 4 & 5). Also, thinning resulted in a slight decline in the abundance of sickle bush and blade thorn, and a slight increase in the abundance of black-thorn acacia, although the differences between the treatments were not statistically significant (Article **III**, Tables 2–4). Tree/shrub counts were significantly and positively related to the centred post-thinning age. As the time since thinning increased by a unit (1 year), the abundance of trees/shrubs also increased. The effect of arboricide aftercare treatment was positive on tree/shrub count per species, although not statistically significant.

3.4 Regeneration of encroaching species following thinning (Article II)

The expected number of trees/shrubs in the 0–1 m height class did not differ significantly between treatments. The thinned areas had a 34% greater abundance of trees/shrub individuals at the 7.2-year mark (Fig 4) (Article **II**, Tables 6 and 7). Further, predictions showed that, for the same height class, it took ∼5 years for counts to equalise between treatments.

Thinning resulted in a significant reduction in the expected number of trees/shrubs for 1–the 3 m height class. The counts recorded in the thinned area were 57.6% of the counts in the non-thinned area. Similarly, in the > 3 m height class, thinning resulted in a significant reduction in the expected number of trees/shrubs (by 90.4%) compared to the non-thinned area. The effect of increasing centred time since thinning was significantly positive on the abundance of trees/shrubs per plot across all height classes (Article **II**, Table 6). Aftercare treatment with an arboricide had a significant effect on the abundance of trees/shrubs. The number of young cohorts in the 0–1 m height class increased, although the inverse was observed in the 1–3 m height class (Article **II**, Table 6). Predictions also showed that counts between treatments may equalise in ∼14 and 15 years for the 1–3 m and >3 m height classes, respectively.

3.5 Effect of treatment on tree/shrub equivalent densities (TE) commonly accepted for the area and approximate woody biomass availability (Article III)

The overall TE densities for the five target species differed significantly between the treatments by approximately 47.3% (non-thinned =1464.05 TE ha^{-1}, thinned = 770.95 TE ha^{-1}) (Article **III**, Table 5 (a) and Figure 3a). These estimates also showed that the predicted TE densities were greater than the minimum levels commonly accepted for a 400 mm rainfall area (i.e. 600 TE ha ^{1}): 59.0% and 13.4% greater in the non-thinned and thinned areas, respectively.

With regard to the overall dry woody biomass of the encroaching species, average biomass in the non-thinned areas were 15.4 tonnes ha^{-1}. The effect of thinning resulted in a significant reduction (to 5.2 tonnes ha^{-1}), which was evident across all study plots (Article **III**, Table 5 (b) and Figure 3b). Increasing centred post-thinning age had a significant positive trend on the mean dry woody biomass estimates.

3.6 Effect of treatment on the woody vegetation structure and habitat sighting lines (Article III)

Of the measured stem diameters, the majority (79.1%) were in the ≤ 6 cm diameter class (Article **III**, Tables 6 and 7, Figure 4). It was evident that the number of trees/shrubs differed statistically between the different stem classes and treatments, Significant differences between treatments existed in the 6–18 cm stem diameter class, with a negative response to thinning. For the other stem diameter classes, the response to thinning was negative, although statistically insignificant.

Thinning resulted in significant modifications to the vertical woody vegetation structure. Non-thinned areas were characterised by tall shrubland (mean height = 1.9 m). The effect of thinning caused a significant reduction in height (~1 m), which led to a short shrubland layer (mean = 0.9 m) in the thinned area. Non-thinned areas were also characterised by a higher canopy area and cover (mean = 50.27 m^2, 44.4%). Thinning treatment resulted in a significant reduction (~57%) in canopy area and cover, which led to a low woody canopy area and cover (mean = 21.62 m^2, 19.1%) (Article **III**, Table 9 (b) and Figure 5b).

The effect of treatment on the sighting line distances resulted in significant differences between treatments. Non-thinned areas were characterised by limited sighting distances (~24.8 m) (Article **III**, Table 9 (c) and Figure 5c), while sighting lines in the thinned areas were much greater (~57.4 m). Post-thinning age had a significant and negative effect on sighting lines.

4 DISCUSSION

4.1 Response of wildlife to thinning (Article I)

This study has revealed that thinning had a positive to neutral effect on the activity patterns of local wildlife. The significant effect of thinning observed amongst the large predators suggests that they are highly responsive to changes in vegetation structure and would increase their activity in relation to prey abundance and ideal habitat structure. Interestingly, thinned areas also showed higher activity patterns of large (19.9%) and medium (41.6%) ungulates. This provides one possible explanation for the considerable occurrence of large predators since they are known to select areas with adequate prey abundance or scavenging opportunities, enhanced hunting efficiency due to the presence of ecotones (habitat edges) created by thinning, which allows concealment while stalking, and provide greater sighting visibility to detect prey (Marker et al., 2018c; Marker and Dickman, 2005; Muntifering et al., 2006; Nghikembua et al., 2016a; Stein et al., 2013, 2011; Wiesel, 2015)

The low (insignificant) captures of other animal types in the thinned area may be due to the significant presence of large predators, which could drive a phenomenon known as the landscape of fear (LOF) (Kohl et al., 2018; Suraci et al., 2016). It was likely that other animal types had reduced their activity or presence in thinned plots due to a perceived predation risk, which could be amplified further by the reduction in tree/shrub cover (see Article **III**), which is used by prey when evading predators. The observed significant positive relationship between the numbers of animal captures and camera trap start time may be due to seasonal conditions since the follow-up period (Apr–Jul) coincided with the end of the growing season, where surface water was abundant and vegetation productivity improved, and which could have caused animal numbers to fluctuate. Results also showed that increasing the survey duration beyond 21 days by a unit (1 day) had a significant positive effect on the predicted animal captures, which could also increase the chance to capture rarely sighted species (e.g. cheetahs, caracal) (Brassine and Parker, 2015). However, increasing the survey duration for an indefinite period may lead to over-counting and may present problems during data analysis.

Post-harvest age and camera placement did not have any significant effects on mean captures. However, it was interesting to note that captures were slightly greater off-trail than on-trail. Wildlife, especially large predators, are known to frequent trails more than random locations (Cusack et al., 2015; Fabiano et al., 2018; Mann et al., 2015) and this was expected to occur in both treatment areas. It was anticipated that there would be more activity along trails, especially in the non-thinned area due to the presence of thickets that impede animal movement.

4.2 Soil physical and chemical properties (Article II)

The results of the soil study revealed that the applied thinning strategy had minimal impacts on soil properties, even 7.2-years post-thinning (**Article II**, Table 2). This may be due to the moderate thinning intensity applied and the perturbations may have declined with time. Of the measured soil properties, the TN content was significantly greater in thinned areas. Thinning has the potential to increase the absorption of heat energy and soil surface temperatures as the bare soil fraction is increased and evapotranspiration is reduced (Shen et al., 2022; Zhang et al., 2018). Also, by thinning dense vegetation, soil moisture content and grass cover is enhanced, and these conditions could enhance OM decomposition and the release rate of soil nutrients, specifically since the harvested tree/shrub stumps and roots left intact in the soil would be greater in the thinned plots (Groengroeft et al., 2018; Weil and Brady, 2017). The substantially greater wildlife activity observed in the thinned area (Article **I**) could also result in the import of nutrients through dung and urine depositions (Nghikembua et al., 2020; van der Waal et al., 2011; Zimmermann et al., 2017). Consequentially, greater TN content in the soils in the thinned area is beneficial since it will stimulate the growth of fast-growing grasses and provide a competitive advantage over woody seedlings (Archer et al., 2017; Kraaij and Ward, 2006).

4.3 Number of observed individuals and species-treatment interactions (Article II and III)

With regard to the abundance and occurrence of encroacher species, the results showed that the most abundant species, sickle bush, was not reduced significantly by thinning, possibly due to the avoidance of small-sized stems, and this may explain the substantial reduction in red umbrella thorn as it is structurally larger (Article **III**, Table 1) (Neke et al., 2006). The significant positive response in the occurrence probability and abundance of umbrella thorn in the thinned areas suggests that thinning has the potential to accelerate regeneration of this species. Other studies have reported successful recruitment of species that were less dominant following the reduction in tree/shrub densities (Haussmann et al., 2016; Smit, 2004). This is due to competition for resources with the other dominant species and because the retained trees/shrubs would increase their reproductive output (Dwyer and Mason, 2018; Smit, 2014) For other species, differences in the occurrence probabilities and abundance between the treatments were statistically insignificant. This may indicate that a longer regeneration period is required for these species to reach levels equivalent in the non-thinned area. It was apparent from these findings that thinning caused a range of responses (positive, neutral, negative) amongst the target species, which were still evident 7.2-years post-thinning.

This research showed that the study area was mainly encroached by sickle bush, followed by black-thorn acacia. This contrasted with previous regional estimates where black-thorn acacia was considered as the main encroacher species in the north-central farmlands (Birch and Middleton, 2017; Smit et al., 2015). Similarly, the expected abundance of sickle bush and black-thorn acacia in this study (Article **III**, Tables 2 and 3) was less than the average regional estimates reported in other studies (Birch and Middleton, 2017; de Klerk, 2004). The discrepancy could be due to errors arising from extrapolating density estimates over larger areas without considering the habitat heterogeneity that exists within the farmland matrix. Sickle bush is known to prefer deep sandy loamy soils, which comprise the majority (65.3%) of soils in the study area, whereas black-thorn acacia prefers hard-surfaced, sandy, rocky substrates or loamy soils, which are uncommon in the study area (Article **II**, Table 2) (Orwa et al., 2009).

4.4 Regeneration of encroaching species following thinning (Article II)

The results showed that the expected number of trees/shrubs in the 0–1 m height class was 34% greater in the thinned areas. This would suggest rapid regeneration of a young cohort (sickle bush and black-thorn acacia) following thinning (Article **II**). Similar patterns have been observed in other studies (O'Connor, 2017) where regeneration was related to species abundance. Further, the rapid regeneration of young cohorts may be due to the above average rainfall (> 444 mm) received in the study area between 2008 and 2012 (Article **II**, Figure 2), to competition due to the reduced tree/shrub densities, which allowed more reproductive output, seedling survival and increased growth rates following thinning (Dwyer et al., 2010; Dwyer and Mason, 2018; Rautiainen and Suoheimo, 1997). Also, animals moving through thinned plots (Article **I**) may also have contributed to recruitment, especially as the nutrient rich seedpods from bush-encroaching species are consumed by livestock and native ungulates and could be spread via dung deposition. Secondary agents, such as dung beetles, could also contribute seed dispersal (Archer et al., 2017).

Tree/shrub abundances in the larger height classes (1–3 m, > 3 m) were significantly reduced in the thinned areas. These results suggest that thinning was effective in reducing the abundance of trees/shrubs even 7.2-years post-thinning (Article **II**, Tables 6 and 7). Previous research has shown that the targeted encroacher species generally experience slow growth rates due to the variable climate, elevated mortality rates (e.g. from drought, frost, fires, herbivory) and limitations in recruitment events determined by exceptional high rainfall seasons (Cunningham and Detering, 2017; Joubert et al., 2017, 2013; Lohmann et al., 2014;

O’Connor, 2017). Therefore, a longer growth period would be expected, and the transition to the upper height classes (1–3 m and > 3 m) may be delayed.

4.5 Effect of treatment on the tree/shrub equivalent densities (TE) commonly accepted for the area and approximate woody biomass availability (Article III)

The overall predicted TE densities for the five target species for non-thinned encroached areas exceeded twice the commonly acceptable threshold for the local area but was much lower than other areas of the country where ~6,000 TE ha^{-1} has been observed (DAS, 2017). It was evident from these findings that the thinning strategy applied was effective in causing a significant reduction in tree/shrub densities, well within the commonly accepted density levels (600–750 TE ha^{-1}) in the area (SAIEA, 2016).

The woody biomass estimates in this study from the non-harvested encroached areas was also much less than the regional average (36.2 tonnes ha^{-1}) from a previous study by Smit et al., (2015). Possible factors for this occurrence include errors arising from the extrapolation of biomass estimates over larger areas, differences in species composition, soil type, climatic factors, management history, as well as methodologies applied in biomass estimation (Chave et al., 2014; Djomo and Chimi, 2017; Feyisa et al., 2018).

4.6 Effect of treatment on the woody vegetation structure and sighting lines (Article III)

Overall, the results in Article **III** suggested that thinning was effective in modifying the dense vegetation structure associated with bush encroachment. The obvious explanation for these results is the considerable reduction in the overall tree/shrub abundance, mainly in the 1–3 m and > 3 m height classes (Article **II**) (Nghikembua et al., 2021). Moreover, sighting lines increased in the thinning treatment. Sighting lines were inversely related to post-thinning age, possibly due to the rapid natural regeneration present in the same study area (Article **II**) (Nghikembua et al., 2021). Previous studies have also shown that retained individuals accelerate their structural growth following a reduction in tree/shrub densities due to competition from strong competitors, which may have occurred in this present study (Brown et al., 2019; Dwyer et al., 2010; Dwyer and Mason, 2018; Smit, 2014; West, 2014). The predicted sighting line in the thinned areas in this study is slightly less than those measured in areas preferred by cheetahs (≥ 62.8 m) reported in other studies in the same region (Muntifering et al., 2006; Nghikembua et al., 2016b). This may be because the vegetation in the other studies was not thinned manually and may have developed from natural disturbances (e.g. fire, natural dieback) or as a consequence of clearing for open grass fields.

The restored vegetation structure would be advantageous as it would restore the soil moisture balance, reduce the suppression effects of woody plants on the herbaceous layer, thereby increasing the likelihood for greater grazing capacity and ease of movement as animals manoeuvre through the habitat (de Klerk, 2004; Groengroeft et al., 2018; Hagos and Smit, 2005; MAWF, 2012; Muntifering et al., 2006; Richter et al., 2001; Smit et al., 2015; Stafford et al., 2017). This may explain why thinned areas were strongly frequented by wildlife, reported in Article **I** of this thesis (Nghikembua et al., 2020).

4.7 Combined discussion for Articles I-III

The thesis aimed to explore the effects of restoration thinning on native wildlife and encroaching woody vegetation, to identify responses and demonstrate the effectiveness of this method (thinning) in reducing bush encroachment in north-central Namibia. A large territory of the Namibian farmland is affected by bush encroachment causing significant loss of grazing capacity, and suitable habitat for open savanna adapted wildlife (SAIEA, 2016). Manual thinning of excess woody densities was applied to control bush encroachment. However, information regarding the responses of this method remains largely unknown towards components of the affected habitat. The theoretical and practical contributions of Articles I-III are discussed by addressing specific aims to examine the effect of restoration thinning towards wildlife (**Article I**), regeneration of encroaching species and soils (**Article II**), the vegetation structure (abundance, biomass, canopy cover) and habitat sighting lines (**Article III**).

The results of Article **I** confirmed that wildlife responses could be predicted in thinned and non-thinned area based on photographic captures. This study documented as predicted, positive responses to thinning amongst all animal types. For large predators the effect of thinning was significant, suggesting that they were the most responsive to the thinning treatment. However, this study found a lower but positive effect amongst all other animal types. The treatments were distinguishable from each other in terms of the vegetation structure (**Articles I-II**) which may be the reason for the observed effect in captures. Non-thinned areas had higher tree/shrub density, with reduced habitat sighting lines which appeared to limit populations of wildlife. In contrast, thinned areas were composed of a lower tree/shrub density, canopy cover and greater habitat sighting lines which appeared to favour wildlife activity and habitat use (Muntifering et al., 2006; Nghikembua et al., 2016a). These results highlight the importance of restoration thinning in counteracting the negative effects associated with bush encroachment. For example, if the habitat is encroached, then wildlife activity will likely be reduced. However, following restoration thinning, positive responses are expected.

It was evident from this study that thinned areas are attractive hotspots for both predators and ungulates. This scenario highlights potential management challenge as to how these areas should be managed sustainably in the long-term. On a typical livestock farmland, thinning is carried out to increase grazing capacity specifically for livestock. Therefore, if previously thinned areas are stocked, the unattended (and vulnerable) livestock could fall prey to predators. In addition, a combination of livestock and ungulates in thinned areas with no proper management may degrade the thinned areas, and thus perpetuate the bush encroachment cycle. These responses suggest the importance of replicating future restoration thinning efforts over larger landscapes to avoid pressures from wildlife such as overgrazing and human wildlife conflict that would increase the risk for rangeland degradation, predator persecutions and economic loss. Specifically, post-thinning management plans that include grazing management, water management and livestock-predator conflict management are necessary.

The results of Articles **II**-**III** confirmed as predicted that there would be a considerable reduction in the abundance of encroaching species, minimal disturbance to soils and significant modification of the vegetation structure. Consequentially, this would create a favourable habitat structure for wildlife, herbaceous growth, and better grazing capacity. Interestingly, thinning also caused varied responses amongst the encroaching vegetation by significantly increasing the occurrence and density of the umbrella thorn and the reduction of red umbrella thorn. The significant increase of the umbrella thorn is an indication of rapid encroachment. For the red umbrella thorn the significant reduction indicates that this species was targeted more than the abundant species and faces a risk of it being overharvested. Further, natural regeneration from encroaching species was rapid, as evidenced by the greater abundance (34%) of young cohorts (0-1m) in thinned areas. These results highlight the importance of restoration thinning in reducing tree/shrub densities. However, the responses (Articles **II-III**) observed highlight several potential management challenges that if not addressed, could negatively affect the sustainability of restoration thinning in the long-term. For example, in Article **II**, rapid natural regeneration was observed and in the absence of post-thinning management, the previously thinned areas will revert to bush encroachment. This could make restoration success to be short lived and increase the costs for bush control as more financial investments would be required for follow up treatment (Eldridge and Ding, 2021). Also, the significant decline in the abundance of the red umbrella thorn (Articles **II-III**) indicates that restoration thinning could impact some species negatively, by altering their population structure and distribution. This further emphasises the importance of future restoration thinning efforts to strengthen their management practices, particularly the development of harvest protocols that addresses adequate harvester training to avoid overharvesting of the most sought species. Also, restoration thinning should not be considered as a once off event and post-thinning management should be prioritised to reduce the abundance of established saplings in previously thinned areas.

4.8 Theoretical and practical contributions to the field

Articles **I-III** have an overall aim to explore the effect of treatment (thinned, non-thinned) towards wildlife, soils, vegetation, and habitat structure. Thus, the findings from Articles **I-III** provide relevant contributions to the fields of environmental management, specifically conservation and restoration of ecosystems to enhance biodiversity. Moreover, these studies respond to Namibia's strategic objectives on the sustainable management of bush resources for the period 2022 – 2027 (MEFT, 2022). This strategy prioritises research and collaboration in order to increase knowledge regarding bush encroachment and its control, and further explore impacts towards biodiversity. This effort would ensure the sustainable utilisation and management of biodiversity resources without compromising the integrity of the environment. Studies of this nature are relevant since they contribute to the knowledge regarding the impacts associated with restoration thinning. Such information is vital to evaluate management actions and inform the design of future restoration efforts.

The findings from the wildlife study (Article **I**) provide relevant contributions to the field on species-treatment interactions, in the context of bush encroachment control aimed at enhancing biodiversity. Previous studies that explored the responses of wildlife to bush control methods focused mainly on herbivores, to the exclusion of predators (Isaacs et al., 2013; Schwarz et al., 2018). Also, these studies utilised different bush control methods that involved mechanical (bulldozing) and the use of fires during the removal of vegetation. Hence, this article implies an original and relevant contribution, because both ungulates and predators were studied, and findings could shed more light on future population trends and ecosystem dynamics in response to restoration thinning. Specifically, the research findings have practical implications and can be directly used to influence the development of effective predator conflict mitigation strategies to reduce potential risks for human-wildlife conflict, predation risks to prey species, and modelling habitat suitability for different species to accommodate habitat requirements for wildlife. Findings from Article **II** provide relevant contribution to the field on effects of treatment (thinned, non-thinned) towards soils as well as natural regeneration of encroaching species since thinning had taken place. To the best of the author's knowledge, this is the first research that has studied the response of five Namibian thornbush savannah woody species and soils in the context of restoration thinning (manual). Previous studies (SAIEA, 2016; Smit, 2001; Harmse et al, 2016) that explored the responses of woody vegetation to bush control methods focused mainly on few species (e.g. sickle bush, black-thorn, and mopane (*Colophospermum mopane*)) to the exclusion of others known to cause encroachment (e.g. red umbrella thorn, umbrella thorn and blade-thorn). Also, these studies utilised different bush control methods that involved unselective mechanised clearing, selective mechanised thinning, mechanical clearing and arboricides and the use of chemicals (selective, nonselective) during the removal of vegetation. Hence, this article implies an original and relevant contribution that could broaden the understanding of the thinning treatment effect towards the soils and woody species. Specifically, the research findings have practical implications towards the management of bush encroached and restored areas and can be used to directly influence the development of protocols for sustainable biomass harvesting to prevent overharvesting of certain species and minimise the loss of soil nutrients as well as post thinning management plans to prevent rapid re-encroachment. Moreover, Article **III** provide relevant contributions to the field on woody species-treatment interactions, as well as the effects associated with the modification of the woody vegetation structure. Specifically, these findings can be used to directly influence the assessments of wildlife habitats to model suitability, species-treatment interactions to identify current conditions and project future population trends and ecosystem dynamics, harvesting impacts towards woody species, and the development of harvesting protocols to ensure that the biomass is harvested sustainably.

5 CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

This study revealed that thinning caused overall positive to neutral effects on wildlife. Large predators were the most responsive, possibly due to the high prey abundance, and ideal habitats for the detection of distant prey, as well as concealment along habitat edges and cover in high grass while hunting. The greater frequency of large predators is a possible explanation for the low captures of other animal types possibly due to fear of predation. However, there could be a potential risk to livestock in these areas if protection is inadequate. As some animals utilised both treatments equally, thinning should aim at the creation of a heterogenous vegetation structure: the creation of open patches ideal for grazers and sprint hunting predators (e.g. cheetah), as well as the retention of dense thickets for browsers and ambush predators (e.g. leopard).

Thinning had a minimal effect on most soil properties possibly due to the moderate thinning intensity applied, and perturbations may have declined with time. Thinning caused overall varied responses (positive, negative) by the encroaching woody species; occurrences and abundance of red umbrella thorn were reduced but were increased for umbrella thorn. This could possibly be due to harvester preferences for trees/shrubs that are structurally larger (in the case of red umbrella thorn), and also because of rapid regeneration due to competition from dominant woody competitors and reseeding by wildlife (in the case of umbrella thorn).

These results showed that thinning has the potential to alter the floristic composition, abundance, and structure of woody species within the local farmland ecosystem. Natural regeneration of encroaching species was rapid: young cohorts (0–1 m) were greater in the thinned area 7.2-years post-thinning than in the non-thinned areas, and are a potential risk for re-encroachment. Overall, thinning was effective in reducing bush encroachment well within the commonly accepted densities for the area. The average difference (10.4 tonnes ha^{-1}) in woody biomass between the treatments showed that biomass could be harvested well within the commonly accepted density range for the area. Moreover, greater sighting lines, ideal for wildlife that rely on longer sighting lines when hunting (e.g. cheetah) or evading predators (e.g. prey species), were restored.

This study revealed important findings with regard to the response of wildlife, vegetation and soils. However, the study is not without limitations. Firstly, only one thinning treatment type (manual, ~50%) was used in this study and a range of responses could be expected dependent on the level of thinning intensity. Secondly, as the results were limited to the study period and to CCF farms, longer term data and replication of the study in other areas is required to fully evaluate the responses of wildlife and vegetation, and the recovery of the soils in the farmland ecosystem.

Future studies and management should consider: (i) long term monitoring of the same aspects studied here to reveal trends that span multiple seasons and areas: (ii) control of established saplings in thinned areas to prevent the loss of open savannah vegetation structure; (iii) harvester training on basic farmland ecology, selection of tree/shrub sizes, species and minimum densities required for retention; (iv) development of allometric equations for local species to reliably predict available woody biomass, and (vi) ongoing thinning efforts to control bush encroachment.

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