Ecological corridors and ecosystem services: potential for climate change adaptation in Johannesburg, Gauteng

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science in the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

NAtcheson.

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26/04/2021

Abstract

Climate change threatens the state of biodiversity and ecosystems worldwide. Furthermore, as urbanisation continues to increase, cities have become even more vulnerable to the impacts of climate change. This makes it imperative for cities to implement climate change adaptation strategies. An Ecosystem Based Adaptation strategy where ecological corridors and the ecosystem services they provide are protected, can potentially increase a city's adaptive capacity. This study investigated the functionality of ecological corridors and their associated ecosystem services within Johannesburg, South Africa, in order to determine if investing in their protection is a worthwhile climate change adaptation strategy for the city.

This study identified two ecological corridors - the Braamfonteinspruit and Modderfontein corridors. A spatial assessment determined that the Braamfonteinspruit corridor consisted primarily of trees, whilst the majority of the Modderfontein corridor consists of planted and natural grasslands. This indicates that both corridors have the vegetation necessary to provide a variety of ecosystem services, including carbon sequestration and temperature regulation. Additionally, both corridors were mostly surrounded by low intensity land uses which helps promote the provision of vital ecosystem services. A vegetation assessment was conducted in both the Braamfonteinspruit and Modderfontein ecological corridors. Vegetation structure, percentage ground cover, composition and species richness was assessed at every study site within each of these corridors. In order to assess species composition, the Braun-Blanquet method was used. Both corridors had a low species richness that included mostly herb and exotic species. Both corridors were mostly covered in grassland and no significant difference was found between different ground cover types in each corridor. In order for both corridors to better provide ecosystem services, species richness would need to be increased.

Three ecosystem services, namely flood regulation, temperature regulation and carbon sequestration, were investigated within both ecological corridors. The Braamfonteinspruit and Modderfontein ecological corridors had relatively low soil compaction measurements and there was no significant difference between their average soil compaction values. This suggests that both corridors have soil that can easily absorb and retain water, thus aiding with flood regulation. However, there was a significant difference found between soil compaction measurements at the different sites along the Braamfonteinspruit and Modderfontein ecological corridors. There was no significant difference between the cooling effect inside and directly outside both ecological corridors, however this may be because the corridors are cooling down surrounding areas. Despite there not being a significant difference between the cooling effect of both corridors, it was found that the Modderfontein corridor, which had more trees than the Braamfonteinspruit ecological corridor, had a slightly higher cooling effect. Clearly both corridors provide the ecosystem service of temperature regulation and due to the fact that surrounding areas are mostly made up of low intensity land-uses, this cool air can flow easily into surrounding areas. Lastly, it was found via two methods that the Modderfontein ecological corridor stores more carbon than the Braamfonteinspruit corridor, which can be attributed to the Modderfontein corridor having more trees which were larger as well as an overall greater green area. Essentially, both corridors can provide carbon sequestration, however larger and an increased number of trees will help increase the provision of this ecosystem service.

Based on the results of this study, it can be concluded that both the Braamfonteinspruit and Modderfontein ecological corridors are functional and provide vital ecosystem services that help the City of Johannesburg and its citizens adapt to climate change. It is recommended that both corridors be formally protected and managed in order to increase plant species richness and tree cover. Using ecological corridors and their associated ecosystem services has the potential to be an effective and long-lasting climate change adaptation strategy for Johannesburg.

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List of acronyms and abbreviations

EBA – Ecosystem Based Adaptation

UHI – Urban Heat Island

CO_2 – Carbon Dioxide

IUCN - International Union for Conservation of Nature

UES- Urban Ecosystem Services

NPAES - National Protected Area Expansion Strategy

GCRO - Gauteng City Region Observatory

GDARD - Gauteng Department of Agriculture and Rural Development

SANBI - South African National Biodiversity Institute

PA - Protected Areas

SA - Sensitive Areas

CBH - Circumference at Breast Height

DBH – Diameter at Breast Height

BA – Basal Area

SE – Standard Error

Chapter 1. INTRODUCTION AND LITERATURE REVIEW

Climate change is one of the main causes of biodiversity loss around the world. Despite actions taken to prevent further climate change, the earth will still experience the inevitable negative impacts (Heller and Zavaleta, 2009).Climate change is currently occurring but it is also becoming more severe (Owen, 2020). Moreover, urbanisation is happening at an increasing rate worldwide. Natural landscapes are being changed drastically and habitats are continuously becoming fragmented (Gómez-Baggethun and Barton, 2013). Urbanised areas are extremely vulnerable to the impacts of climate change such as flooding, heat waves, diseases and species extinctions (Tanner *et al.*, 2009). Clearly, there is a need for urbanised areas to implement climate change adaptation strategies that will protect against these negative impacts (Laros *et al.*, 2013). There is also a particular need for climate change adaptation within poorer urban areas with a large human population (Tanner *et al.*, 2009).

It is extremely vital for cities to initiate climate change adaptation strategies (Owen, 2020). A potential strategy could be Ecosystem Based Adaptation (EBA) where natural biodiversity, ecological corridors as well as ecosystem services are utilised and protected in order to counteract negative climate-related impacts (Laros *et al.*, 2013). An ecological corridor can be the solution to habitat fragmentation in a city (Closset-Kopp *et al.*, 2016) which would allow for species adaptation through dispersal and/or migration in response to climate change (Keeley *et al.*, 2018). Furthermore, protection of ecosystem services is another potential method to increase climate change adaptation and resilience within an urban environment (Gómez-Baggethun and Barton, 2013). Clearly, ecological corridors and the ecosystem services that they provide link societal and ecological aspects within an urbanised area and have the potential to improve human well-being, species survival and climate change adaptation (McPhearson *et al.*, 2014). In the unique urban areas of Johannesburg in South Africa, resources need to be invested into climate change adaptation strategies that will be effective. Therefore, this research will investigate the functionality of ecological corridors and their associated ecosystem services in order to determine if investing in their protection may provide an efficient and effective method for climate change adaptation in Johannesburg.

1.1 Climate change and adaptation

Climate change is both the direct and indirect result of anthropogenic activities (Hulme, 2005) and it has massive impacts on the economy, human health and ecosystems (Owen, 2020). For example, increasing carbon dioxide emissions through the large-scale use of unclean energy production has led to increases in global average temperatures and widespread desertification (Chang *et al.*, 2010). In response to climate change impacts, the distribution ranges of many plant and animal species are expected to shift. An example of this is the increased poleward distribution of birds in the United Kingdom in response to climate change (Gillings *et al.*, 2015).

The danger with species range shifts is that species can move out of conservation areas and into dangerous human environments, further increasing the rate of species loss. For example, the Chinese giant salamander (*andrias davidianus*) will have a decreased range in the future as a result of climate change (Zhang, 2020). Furthermore, climate change is predicted to become one of the main drivers of biodiversity loss. This can be through a rise in carbon dioxide levels in the atmosphere (Heller and Zavaleta, 2009) or through climate change related impacts such as frequent fires (Cahill *et al*., 2013)

Clearly, there is a need for society to deal with the impacts of a changing climate. However, actions against climate change are extremely complex, particularly in third world countries where financial resources are limited. Additionally, the multifaceted and unpredictable impacts of climate change make it difficult to create long term and effective solutions. The conservation of ecosystems is a potential method to adapt to the impacts of a changing climate, however conservation strategies cannot be too expensive or slow and need to result in the long-term protection of these ecosystems (Townsend and Masters, 2015). An example of a successful conservation action is the preservation of coral reefs found in the Flower Garden Banks National Marine Sanctuary located in the Gulf of Mexico (Gil-Agudelo *et al.*, 2020).

The already extreme impacts of climate change are only made worse by poor and uninformed management strategies. For example, species that are not able to disperse from areas affected by climate change may need to be translocated instead of being unsuccessfully managed through increased habitat connectivity (Hulme, 2005). Furthermore, the successful mitigation of climate change through alternative energy sources and decreased use of fossil fuels is also possible. Despite the effort to conserve ecosystems and mitigate negative effects, the fact is that climate change is occurring and will continue to occur, impacting the lives of all species on Earth. This means that adaptation must become one of the main responses to these impacts (Hulme, 2005). However, before adaptation can be truly effective, various climate change scenarios need to be looked at, communication and harmonisation of regional establishments must occur and increased spatial and temporal outlooks are necessary (Heller and Zavaleta, 2009).

The distinction between climate change adaptation and climate change mitigation is that mitigation aims to reduce the change in climate systems, whereas adaptation involves preparing for these changes. When it comes to mitigation strategies, there is often a long time delay before it accomplishes its objectives, making it vital for adaptation strategies to be put in place. Clearly, climate change is going to have inevitable consequences on the environment which means that adaptation needs to take place in order for the environment, people and animals to cope with the impacts (Hulme, 2005). Scientists and governments must communicate to highlight the areas and species most vulnerable to these impacts, determine the probability of the impacts and highlight different adaptation strategies that need to be implemented (Hulme, 2005).

1.2 Climate change adaptation

The concept of adaptation has been used and researched in multiple disciplines. In the context of climate change it can be understood as a social-ecological system altering when faced with current and future risks and impacts of a changing climate (Moser and Ekstrom, 2010). In terms of ecosystems, strategies for adaptation need to result in ecosystems being cared for in a flexible manner, taking advantage of species' natural plasticity and decreasing both societal and ecological stresses that will be worsened by climate change (Hulme, 2005). These strategies should strive to make use of potential prospects that can result in resilience and can be implemented on a short or long-term basis (Moser and Ekstrom, 2010). It should be noted that, before an adaptive strategy is formulated or put into place, the exact effects of a changing climate on a specific ecosystem or species must be investigated and made clear (Hulme, 2005).

The use of adaptation science gained traction in the beginning of the 21st century as societies and governments across the world started recognising the reality of climate change

(Heller and Zavaleta, 2009; Moser and Ekstrom, 2010). This has resulted in climate change adaptation becoming incorporated into both national and international policies as well as strategies which allow governments and conservation managers to invest in and implement adaptation to climate change within a range of environments in order to protect ecosystems and species (Townsend and Masters, 2015). An effective method for protecting species is to implement strategies that aim to increase the adaptive capacity of species. Adaptive capacity refers to increasing survival rates of animals as well as developing ecosystem resilience by enhancing the capacity to counter variations in the environment (Townsend and Masters, 2015). For example, planting functionally rare species can help increase the adaptive capacity of a forest (Aquilué *et al.*, 2021). Adaptation that takes place locally will most likely be a mixture of direct actions and capacity expansion (Laros *et al.*, 2013). It could make use of systems already present in the environment such as wetlands and their associated services (e.g. water purification), typically referred to as soft ecosystem based approaches, or to make improvements to infrastructure (building dam walls), known as hard ecosystem based approaches, or can be a mixture of these two (Laros *et al.*, 2013).

There used to be the notion that developing countries were more susceptible to climate change impacts and were less capable of adapting when compared to developed countries. However, the impacts of climate change on developed countries such as Australia and America have contested the notion that wealthier countries have a better adaptive capacity (Moser and Ekstrom, 2010). Clearly, the issues surrounding the adaptive capacity of both poor and wealthy countries highlight adaptation barriers (Moser and Ekstrom, 2010). One of the main issues is misinterpreting environmental and species responses to climate change. Furthermore, he issue of putting in place strategies that in actual fact should safeguard economic welfare instead of protecting the environment is also far too commonplace (Hulme, 2005). Adaptation plans often do not take into consideration social science and mainly consider ecological elements (Heller and Zavaleta, 2009). Before a strategy is implemented, adaptation planning is required. This planning needs to be comprised of key steps where scientists, government officials and society work together. In order to plan for adaptation practically, the type of management procedures in place as well as the effects they are having on the environment need to be examined (Heller and Zavaleta, 2009).

In South Africa, climate change increases the risk of destroying ecosystem services which many people, especially those living in rural areas depend on for their livelihoods (Sigwela *et al.*, 2017).Adaptation to climate change is important in South Africa because economic and social resilience are dependent on well-functioning ecosystems. South Africa has adopted an Ecosystem Based Adaptation approach as a method to adapt to future climate change impacts (DEA and SANBI, 2017). This approach focuses on societal welfare and aims to combine typical conservation strategies with ecosystem services into adaptation plans. The overarching goal of this adaptation approach is to ensure ecosystems continue to deliver vital services that benefit citizens and improve socio-ecological resilience to climate change impacts (DEA and SANBI, 2017). Ultimately, when ecosystems are protected, all of the essential services that they provide to humans are preserved, thus promoting people's well-being in the face of climate change (Laros *et al.*, 2013). Examples of EBA include managing wetlands in order to maintain water quality as well as the preservation of forests which will control the movement of water in order to decrease the risk of floods (Munroe and Jenner, 2019).

1.3 Urbanisation

Half of the current human population on Earth live within urban areas and this number is estimated to increase to two thirds by 2050 (Gómez-Baggethun and Barton, 2013), with urbanisation increasing dramatically in developing countries (Cilliers *et al.*, 2014). In terms of altering landscapes and ecosystems, urbanisation is considered to be the most intense and long-lasting form of change. Urbanisation has led to cities having large human populations as well as built infrastructure, creating a unique urban ecosystem (Gómez-Baggethun and Barton, 2013). Ecosystems are classified as various species interacting with non-living elements in order to survive. When it comes to an urban area, there are often many different types of ecosystems in contact with each other which means that an urban area can be classified as one whole ecosystem or a variety of different ecosystems (Bolund and Hunhammar, 1999). An urban ecosystem is mainly made up of buildings with a large human population. There are elements of the natural environment within these ecosystems such as lakes, gardens and parks (Gómez-Baggethun and Barton, 2013). These natural elements contribute to the health and well-being of the population.

Rapid urbanisation negatively impacts health, security and environmental resources (Cilliers *et al.*, 2014). In terms of the environment, urbanisation can lead to an Urban Heat Island (UHI) effect which refers to the higher temperatures that occur within an urban area compared to rural areas. This is directly related to the type of land uses within cities and the small amount of green areas, the surface properties in the city such as surface roughness and the heat that is released by human activities. It is also more prevalent in areas towards the centre of the urban island which are usually considerably hotter than areas on the outskirts of the city. The UHI has devastating consequences for human health and can often result in death due to heat stress (Dang *et al.*, 2018). Besides the UHI effect, urbanisation can also lead to greater levels of runoff and flooding because of water resistant surfaces spread throughout cities which do not allow for water infiltration. It can increase Carbon Dioxide (CO_2) emissions through industry and often results in the loss of many naturally occurring animal and plant species and an influx of alien invasive species (Bryant, 2006). Urbanisation also leads to variability in wind speed, soil moisture and humidity. Additionally, the soil found in urbanised areas tends to be extremely polluted (Bryant, 2006). In order for cities to be built and to expand, natural ecosystems are often fragmented, thus negatively impacting on the biodiversity of the area. This fragmentation together with the clearing of naturally occurring vegetation and increased levels of exotic species negatively impacts biodiversity (Bryant, 2006). According to Akubia *et al*. (2020), ecosystem goods and services throughout Africa are at risk due to urbanisation that accelerates land cover changes.

Climate change poses a threat to urban areas and all organisms living inside a city. Climate change leads to a city having to deal with diseases, pollution as well as flooding (Tanner *et al.*, 2009). These risks are exacerbated within urban areas of developing countries due to the lack of financial resources to deal with climate related issues, high population numbers, informal settlements and lack of infrastructure. The impacts of climate change together with the impacts of urbanisation create a problem for governments across the world (Tanner *et al.*, 2009). There is an urgent need for governments to take control of urban development now in order to protect themselves from future climate change impacts (Laros *et al.*, 2013). It is important to note that climate change adaptation strategies for urban areas will not be uniform as different places will have strategies best suited for that particular environment and jurisdiction (Scott and Lemieux, 2005; Laros *et al.*, 2013).

Clearly, there are issues related to urban climate change adaptation but despite this, there has been more focus on adaptation within rural areas. The reason for this seems to be because people living in the rural areas are highly dependent on natural resources that are sensitive to climate change. However, urban areas are often not considered in climate change adaptation planning, even though they are at risk due to poorly planned development. There is a need to further investigate the climate sensitivity as well as climate change adaptation within urbanised and highly populated cities (Tanner *et al.*, 2009).

1.4 Ecological corridors

Rapid urbanisation has resulted in the loss of plant and animal species as well as their habitats (Austin, 2012). Schmidt *et al.* (2020) conducted a study on the impact of urbanisation on North American mammals. This study concluded that not only are there smaller numbers of mammals situated within urban areas but that these mammals have decreased genetic diversity as a result of inbreeding (Schmidt *et al.,* 2020). Furthermore, the construction of cities for human dwellers has significantly changed landscapes through fragmentation. When fragmentation occurs, patches of natural land become isolated, which in turn negatively impacts the plant and animal biodiversity within them. In order for the natural areas within cities to remain functional and biologically diverse, they need to become interlinked and these ecological links need to be protected (Nor *et al.*, 2017). The reason that connected natural areas will promote biodiversity in the city is because species will have the means to travel between these pockets of natural vegetation, thereby decreasing genetic isolation. It also allows species to move to new habitats when theirs is being impacted by development or pollution (Closset-Kopp *et al.*, 2016).

Natural areas, ecological connections and buffer zones all form part of an ecological network. The vegetation in an ecological network can be fully natural, restored or semi-natural (Nor *et al.*, 2017). The negative impacts of fragmentation such as loss of biodiversity and habitat isolation can be countered with ecological networks. When animals are not isolated, gene flow can occur, allowing their populations to persist in the urban area (Closset-Kopp *et al.*, 2016). Trying to make urbanisation more sustainable can involve enhancing and protecting natural areas in a city. In order to promote the preservation of biodiversity in a city, there needs to be an ecological network throughout the urban area that consists of well-connected green areas. In order to maintain an ecological network, the city needs to have protected natural areas which are interconnected by pathways suitable for all species within the city (Nor *et al.*, 2017).

Ecological corridors allowing for sustainable development (Chang *et al.*, 2010) is a concept that has appeared in several topics related to landscape ecology, ecological planning and urban ecology (Peng *et al*., 2017). Within the urban environment, an ecological corridor would be made up of natural areas, parks and rivers/streams, otherwise known as the green and blue belts. The green belt is vital for a healthy city as it contributes to cleaning the air and regulating temperatures. The blue belt is an important source of water and evaporation (Chang *et al.*, 2010). The ecological corridor concept was initially defined by biologists as a proposed solution to fragmentation (Peng *et al.*, 2017). This idea for solving the negative impacts of fragmentation was highlighted by Wilson and Wilson in 1975 after which the International Union for Conservation of Nature (IUCN) identified ecological corridors as a conservation method to be used across the world. The initial idea of the ecological corridor to be purely for ecological conservation has changed to become part of the ethos and beauty of a city (Peng *et al.*, 2017). Ecological corridors are not simply meant to connect natural areas but are intended for many different types of uses. These include running trails, vegetable gardens, picnic spots, dog parks, bird watching and of course a habitat for animals (Austin, 2012). Ecological corridors help mitigate human related impacts and can decrease environmental degradation (Peng *et al.*, 2017). They can contribute to ecosystem functioning and decrease pollution and erosion (Curcic and Djurdjic, 2013). Furthermore, the vegetation in the ecological corridor can improve the quality of the urban environment by cleaning the air, decreasing noise pollution and regulating temperature. They also provide an area for water filtration and promote overall biodiversity in an urban area (Rocha and Ramos, 2012)

When ecological corridors have parallel/linear ecotones, the uses for these corridors will increase. It should be noted that the capacity of corridors will be affected by their structure such as extent, compactness and breadth (Austin, 2012). Ecological corridors can have different widths, however the greater the width of the corridor, the more beneficial it will be for maintaining a high habitat standard (Peng *et al.*, 2017). Corridors with greater widths reduce edge effects and provide more space for various ecosystem features (Cook 2002). Within an urban area however, it is difficult to have wide corridors as there is limited space (Peng *et al.*, 2017).

A study that took place in Shenzhen City, China concluded that a river corridor should have a width of 100 m, whereas a coastal corridor should be 260 m in width and a shelterbelt corridor should be 150 m (Li *et al.*, 2003). According to Zhu *et al.* (2005), the width of ecological corridors is subject to the structure and function of the specific corridor and is also related to the type of flora in the corridor, the length of the corridor, target fauna found within the corridor as well as the type of land uses that take place around the corridor. Kubei (1996) states that a corridor found at a neighbourhood level should have a minimum width of 10-20 m. However, Peng *et al.*, (2017) states that, owing to the variety of environmental issues in urban environments, there is no specific width for ecological corridors (Peng *et al.*, 2017).

In a review of various studies, Hulme (2005) found that it was highly recommended that adaptation to climate change should involve increasing ecological connectivity. There are however several concerns when considering the use of ecological corridors. Conservation has restricted means, therefore it would make more sense to invest resources into safeguarding expansive natural areas instead of investing in the establishment of ecological corridors (Bryant, 2006). Furthermore, corridors can cause the movement of invasive species into a new area, affecting the naturally occurring biota (Heller and Zavaleta, 2009; Townsend and Masters, 2015). There is also an issue with regards to setting up and maintaining ecological corridors because of private property rights (Bryant, 2006). In order to implement connectivity in an urban environment, there has to be harmonisation between conservationists, citizens, local government as well as cooperation over many jurisdictions. The ways in which this could work smoothly need to be identified in order for connectivity to be implemented successfully (Heller and Zavaleta, 2009).

In order for corridors to be effective, there has to be a goal of trying to connect the landscape. This involves different parties working together, citizens need to be involved, species that are more sensitive to climate change need to be kept in mind, the different uses of the corridors need to be acknowledged, the conservation of ecological corridors needs to be regulated and ecological models for the arrangement of the ecological corridors must be developed (Keeley *et al.*, 2018). Most importantly, ecological corridors must decrease fragmentation within an urban environment (Bryant, 2006).

1.5 Ecosystem services

The Millennium Ecosystem Assessment defines ecosystem services as the advantages that people gain from a functional ecosystem (Gómez-Baggethun and Barton, 2013), as well as the naturally occurring benefits to economic and social structures (Atif, 2018). However, this term can be understood differently throughout several fields of study (Cilliers *et al.*, 2013). Ecosystem services can be categorised into four main groups, namely provisioning, cultural, regulating and supporting services (Atif, 2018). Provisioning services refer to the physical elements provided by ecosystems, whereas cultural services refer to both the physical and immaterial benefits from nature. Regulating services include processes that control environmental conditions and supporting services are needed to ensure the supply of different ecosystem services (Martínez-Harms and Balvanera, 2012). Examples of regulating services would be flood regulation, climate regulation and carbon sequestration. Provisioning services include water and food production, cultural services include aesthetics and recreation and supporting services include the cycling of nutrients (Cilliers *et al.*, 2013). It should be noted that these services can either be market goods like food as well as non-market goods such as air purification (McPhearson *et al.*, 2014). Furthermore, ecosystem services apply to both the indirect and direct gains from the environment (Cilliers *et al.*, 2013). The services that people do not directly benefit from are still vital to support the ecosystems that people get direct benefits from. An example of this would be pollination (Bolund and Hunhammar, 1999).

Urbanisation's increasing pressure on ecosystem services is particularly worrisome, especially since one cannot separate a city from the environment in which it is built. Ecosystem services can differ across cities owing to specific climates and sizes (Bolund and Hunhammar, 1999). Despite this, there are certain ecosystem services that typically classify an urban environment, referred to as Urban Ecosystem Services (UES) (Atif, 2018). It is true that ecosystem services such as noise reduction and urban cooling are vital within a city's ecosystem, however the importance of these UES can vary between cities. For example, in a city that suffers from air pollution like Santiago, Chile, air purification is of vital importance (Gómez-Baggethun and Barton, 2013). Gómez-Baggethun and Barton (2013) identified 11 important ecosystem services within urban areas, namely food supply which could take the form of urban farming (community garden), runoff mitigation and flood control, temperature regulation, noise reduction, air purification, control of environmental extremes, treatment of wastes through filtering water in ponds and through the decomposition of organic wastes, climate regulation, recreation and lastly animal sightings.

Clearly, climate change adaptation and resilience within urban areas rely on ecosystem services. This includes the urban services of air purification/carbon sequestration, temperature regulation and runoff mitigation/flood regulation (Gómez-Baggethun and Barton, 2013). Trees in cities provide air purification services such as carbon sequestration by taking up carbon dioxide during the photosynthesis process and then retaining it as biomass (Nowak *et al.*, 2013). A study from the United States investigated the national carbon storage and sequestration values of trees and found that about 643 million tonnes of carbon are stored within the natural and urban forests (Nowak *et al.*, 2013).

Flood regulation within a city is decreased when impenetrable pavement cover is increased as it hinders water from infiltrating into the soil. Moreover, when trees are present, the speed at which rain water hits the ground is lowered as the tree canopies will slow it down, giving the ground more time to absorb water instead of flooding. Green surface areas also decrease the amount of water that is lost into storm water drains in a city, again reducing the risk of flooding (Gómez-Baggethun and Barton, 2013). A study that took place in

Southampton, United Kingdom, found that many gardens attached to people's homes had been paved over and converted into areas to park their cars. This has taken place in many homes across the city owing to an increase in the number of people owning cars and having limited parking space. This study investigated the effect that this increase in impermeable surface had on flooding in the area and found that, as the impermeable surfaces increased over the years, the volume of water that needed to be attenuated also increased. This highlights the importance of having green areas to provide the ecosystem service of flood regulation (Warhurst *et al*., 2014)

The UHI can be combatted through the ecosystem service of temperature regulation. This service can be provided by vegetation in the urban environment via evapotranspiration and shading. The UHI occurs in Cairo, Egypt as there is little vegetation which ultimately causes increased usage of air cons throughout the city. According to Aboelata *et al.* (2020), trees should be planted in urban and dense areas of the city in order to decrease temperatures and electricity usage.

Important ecosystem services are provided by ecosystem features present within ecological corridors. As stated previously, corridors are not solely meant to increase connectivity (Austin, 2012) but can benefit the surrounding urban environment as they are natural areas with trees and vegetation capable of providing the above-mentioned ecosystem services of carbon sequestration, flood regulation and temperature regulation (Rocha and Ramos, 2012). Trying to attain sustainability and resilience within an urban environment is extremely complicated due to the difficulties of urban areas having a social-ecological environment that needs to be preserved. This is where ecosystem services come into play as they connect both the ecological and social needs of the urban environment and can benefit both aspects at the same time. They also increase the resilience of a city to the impacts of climate change, allowing people to continue benefitting from ecosystem services. This means that the natural environment needs to be integrated and maintained within a city. With this in mind, the protection of biodiversity within an urban environment is vital as it is responsible for providing essential ecosystem services and should be taken into account for urban planning as well as policy making. However, the connection between people's wellbeing and biodiversity in a city is often misunderstood and ignored (McPhearson *et al.*, 2014). Adaptation to climate change in a city environment needs to allow people as well as the environment to adjust to current or future impacts. In essence, the urban environment needs to become less exposed to impacts. Furthermore, efforts to increase adaptation can incorporate methods that decrease the amount of climate related effects such as maintaining ecosystem services or other methods that promote the adaptive capacity of the city (van de Sand *et al.*, 2014).

1.6 The Greater Johannesburg area

South Africa has nine provinces of which Gauteng is the smallest, despite having a large population. This population experiences the fastest growth, resulting in increased urbanisation (Pfab *et al.*, 2017). Gauteng Province has Highveld grasslands and savanna vegetation (Pfab *et al.*, 2017). Within Gauteng is the City of Johannesburg, one of the biggest and wealthiest cities in Africa. However, the continuous need for development in Johannesburg has led to rapid urbanisation and the challenges that come with it. Urbanisation, together with population growth in the city, have led to degradation of an environment already under pressure to meet the requirements of its citizens (Keeley *et al.*, 2018).

In order to try and reduce the level of environmental degradation, a twenty-year National Protected Area Expansion Strategy (NPAES) was created in 2008. This strategy is aimed at increasing the number of protected areas throughout South Africa in order to promote climate change resilience and sustainability. This strategy identified priority areas for protection and gave methods to go about implementing it. South Africa needs this type of strategy in order to protect biodiversity with limited resources. Protected areas are extremely important parts of ecological corridors in South Africa (DEA, 2016) as they prevent the destruction of these natural areas in favour of further urbanisation in the city.

According to the recent National Biodiversity Assessment, the biodiversity in South Africa has become increasingly affected by climate change impacts. There have been negative effects on the structure and functions of various ecosystems in the country as well as high levels of plant species extinctions such as the Clanwilliam cedar (*Widdringtonia cedarbergensis)*. The reality in South Africa is that widespread natural degradation as well as invasive species are becoming more prominent due to the impacts of climate change (SANBI, 2019). It is estimated that by 2050, the average temperature in South Africa will have risen by 2–4°C. Specifically, in Johannesburg temperatures are expected to increase by 2.3°C in the short term and by 4.4°C in the long term (City of Johannesburg, 2018). The country has also had to deal with extreme weather events resulting in flooding, droughts and wildfires which will only continue to increase with climate change (SANBI, 2019). With this in mind, the National

Biodiversity Assessment suggests that the country needs to have well-functioning ecosystems in order to combat the increasing impacts of climate change. It is put forth that, by increasing connectivity in the country, the ability of various ecosystems to adapt to climate change will be enhanced, ultimately helping the people of South Africa to become resilient to these inevitable impacts (SANBI, 2019)

1.7 Aim and Objectives

As a result of climate change, the City of Johannesburg has and will continue to experience increasing temperatures, rainfall, humidity and extreme weather events amongst other impacts (CCAP, 2009). Given the risks that Johannesburg faces in terms of climate change, the aim of this research was to assess the current state of ecological corridors and ecosystem services in the city of Johannesburg and their potential for climate change adaptation.

Research objectives:

1. To assess land cover and connectivity of two ecological corridors in urban Johannesburg, namely the Braamfonteinspruit and Modderfontein corridors;
2. To assess the current state of three ecosystem services within the ecological corridors, namely flood regulation, temperature regulation and carbon sequestration;
3. To discuss the potential of ecological corridors and ecosystem services for climate change adaptation.

Chapter 2. METHODOLOGY

2.1 Study area

Johannesburg is situated within Gauteng Province, South Africa (26.2044° S, 28.0456° E; Figure 1). The city currently has a high population number of 4.4 million people, with the majority of the population being 19-39 years old. Johannesburg contributes significantly to the Gross Domestic Product (16%) and to employment (12%) in the country. Furthermore, this city is known as South Africa's financial capital with 64.7% of homes having access to piped water and 90.8% with access to electricity (City of Johannesburg, 2018).

Johannesburg has 17 nature reserves and over six million trees in gardens and along roads. The city also has about 1000 ha of green areas and there are rivers (12) and dams (106) present throughout (City of Johannesburg, 2018; Figure 2). Average temperatures in the city during rainy summers range between 17°C and 28°C and between 5°C and 19°C during dry winters (SAWS, 2016). Gauteng Province is mostly made up of the grassland biome (SANBI, 2019) and areas of natural grasslands can still be found within urbanised parts of Gauteng (Grobler *et al.*, 2006).

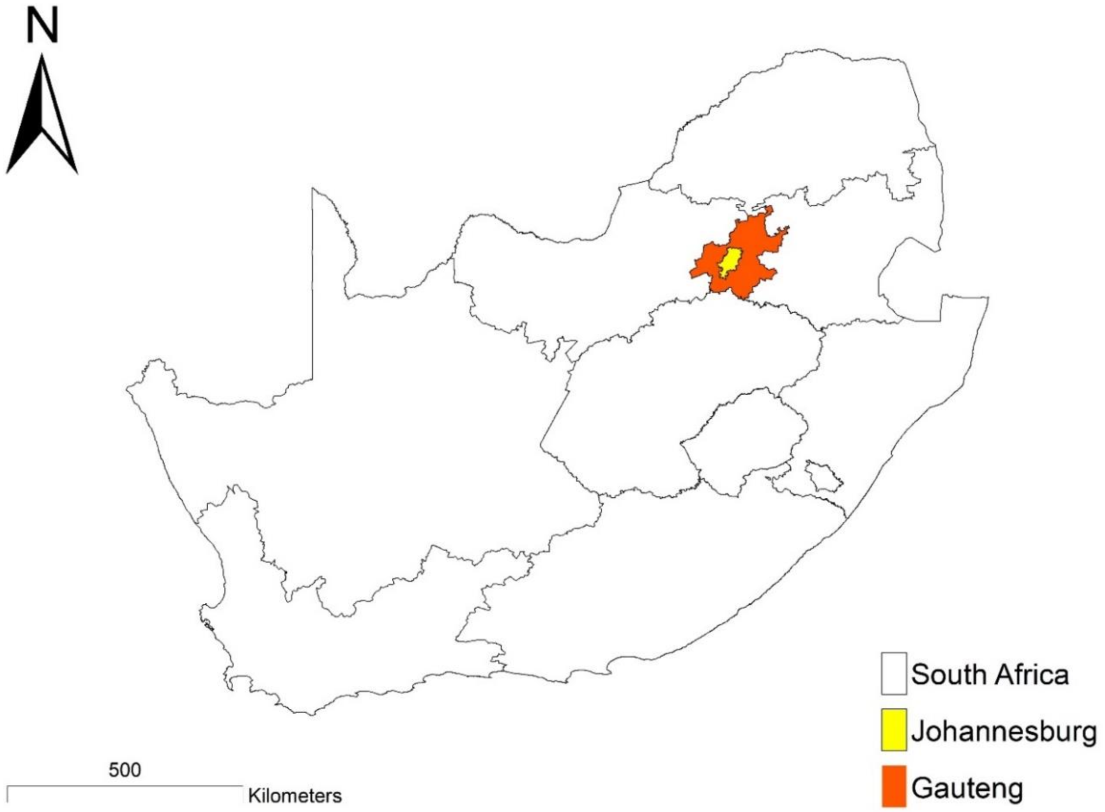

Figure 1: The city of Johannesburg in Gauteng province, South Africa

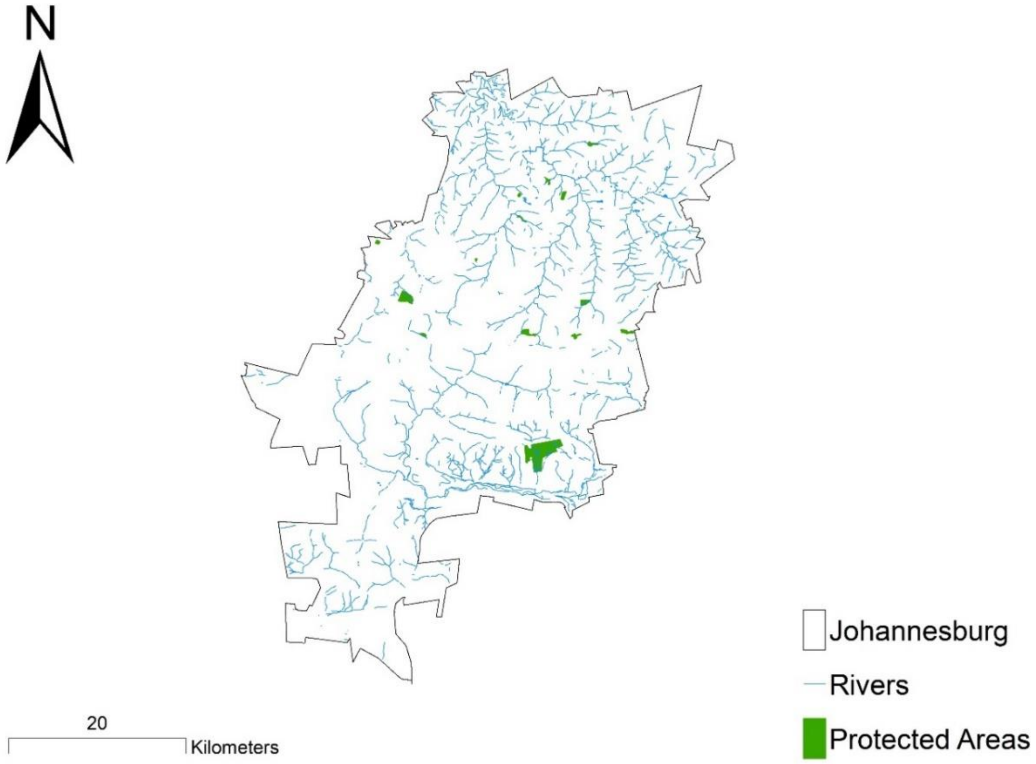

Figure 2: Rivers, dams and protected areas within Johannesburg, Gauteng province, South Africa (GDARD, 2013)

2.2 Corridor identification and spatial analysis

Five potential ecological corridors within the boundaries of Johannesburg were identified using Google Earth Pro v7.3.3 (2020). Austin (2012) investigated average flushing distances of different species and concluded that corridors between 10 - 30 m in width are needed for various animal species habituated to human disturbances. Therefore, five corridors with a minimum width of 10 m were chosen within Johannesburg. The area, average width and length of each corridor was determined using Google Earth Pro (2020) and ESRI's ArcGIS (2017) (Figure 3). After these corridors were assessed, two corridors with the greatest width and area were selected for study. This was done as, according to Forman (1995), corridors with a larger width and area have more ecological advantages. The chosen corridors were located along the Braamfonteinspruit and within the Modderfontein area.

Gauteng land use shapefiles (©GEOTERRAIMAGE – Land cover/use 2.5m 2014) from the Gauteng City Region Observatory (GCRO) and ESRI's ArcGIS (2017) were used to assess the types and total percent of different land uses (Table 1) within both corridors as well as surrounding the perimeter of the Braamfonteinspruit and Modderfontein ecological corridors. Using Google Earth and Arc GIS, I created a shapefile of land that directly surrounded each corridor. Essentially, this shapefile consisted of land that was in between the border of the ecological corridor and a road. The land uses within and surrounding the corridors were classified into low intensity and high intensity land uses. Low intensity land uses include trees, shrubs, wetlands and other natural features, whilst high intensity land uses include man-man structures such as roads, mines and buildings. The total percentage of high and low intensity land uses within and surrounding both corridors was then calculated. Shapefiles from the Gauteng Department of Agriculture and Rural Development C-Plan 2 (GDARD, 2013) were used to assess if and to what extent the ecological corridors fall within Protected Areas (PA), Sensitive Areas (SA) or Conservancies (Table 2). The presence of rivers, ridges and wetlands within the corridors or within areas 1 km from the corridors were also determined using the C-Plan.

Table 1: Definition of various land-uses according to GEOTERRAIMAGE (2014)

Land-use	**Definition**
Commercial	Offices, churches, train stations, health facilities, government, commercial, can include residential flats
Industrial	Industrial, power stations
Residential	Houses, flats, hostels, townhouses
Sports & Recreation	Sports fields, not including school sports fields
Buildings	Buildings of unknown classification
Thicket, Bushland, Bush clumps	Land covered in Thicket, Bushland, Bush clumps
Roads	Roads
School grounds	School buildings and sport grounds

Land-use	**Definition**
Smallholdings	Small farms and smallholdings
Degraded natural vegetation	Degraded natural vegetation
Water	Water features such as lakes, rivers etc. does not include wetlands
Wetlands	Wetlands
Golf Courses	Golf courses
Open	Open areas
Grassland	Natural and planted grasslands
Trees	Trees and forested areas
Bare Rock & Soil	Natural surfaces
Rail	Rail and rail lines
Cultivated, Commercial, Dryland/ Rainfed	Cultivated, Commercial, Dryland/ Rainfed land areas
Mines & Quarries	Mine buildings
Built up	Areas of unknown classification, includes airports, holiday buildings, cemeteries etc.
Township	Includes RDP housing and townships

Table 2: Definitions of sites according to the Gauteng Department of Rural Development (2013)

Sites	Definition
Irreplaceable sites	Sites that are vital for achieving biodiversity conservation goals
Important sites	Sites that help conserve biodiversity
Protected areas	Level 1 Protected Areas - Areas that are written in the legislation for biodiversity protection AND have a management plan Level 2 Protected Areas - Areas that are written in the legislation for biodiversity protection OR have a management plan
Reserved sites	Level 1 and level 2 Protected Areas

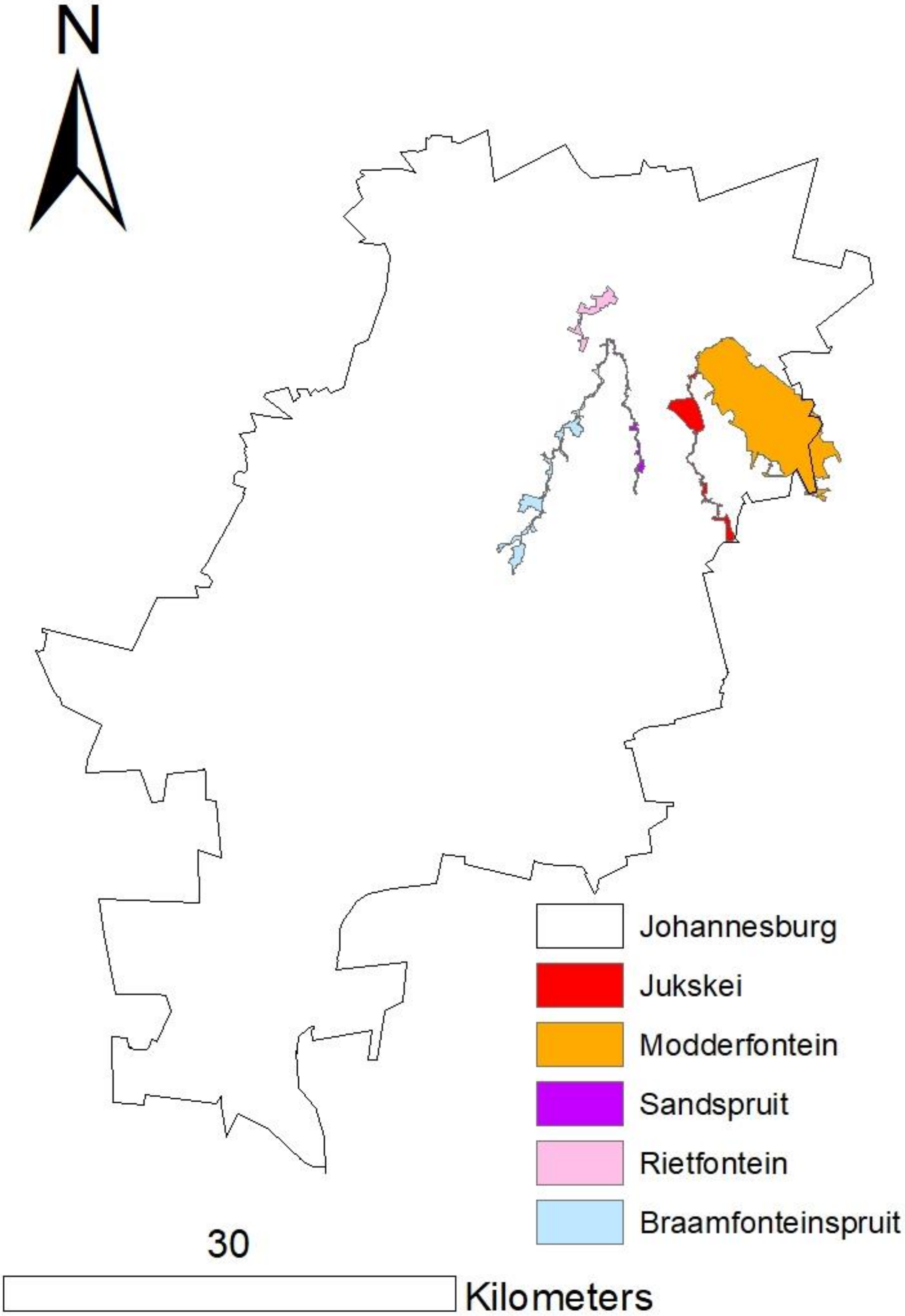

Figure 3: Five ecological corridors within Johannesburg, South Africa

2.3 Site selection and vegetation assessment

On Google Earth Pro v7.3.3 (2020), a placemark was dropped every two kilometres along the middle of the Braamfonteinspruit; each placemark represented a study site (Figure 4). In total there were nine study sites along the Braamfonteinspruit. On Google Earth I drew a 100 m^2 square around each placemark. I then wrote numbers (starting from 1) on each 1 cm^2 block of a grid. I placed this grid over the first square I had drawn on Google Earth. Next, I ran a random number generator. I used the number that the generator provided to choose a block on the grid (Waugh, 2000). For example, if the random number generator provided the number five, I would use the block on my grid that was labelled as number five. I then put another placemark in the centre of the chosen block and recorded the co-ordinates. I repeated this method at each of the nine placemarks. At the end of this process, I had recorded nine co-ordinates along the Braamfonteinspruit. When I went to the Braamfonteinspruit to conduct my vegetation analyses I used a GPS to find the location of the first co-ordinate and then set up a 200 m^2 quadrat around this location. I repeated this process at each of the co-ordinates. In total, I set up nine quadrats along the Braamfonteinspruit. As per Grobler *et al.* (2006) who conducted a vegetation survey within urban open spaces around Gauteng, made up mostly of grasslands, the size of the sample quadrat was set to 200 m^2.

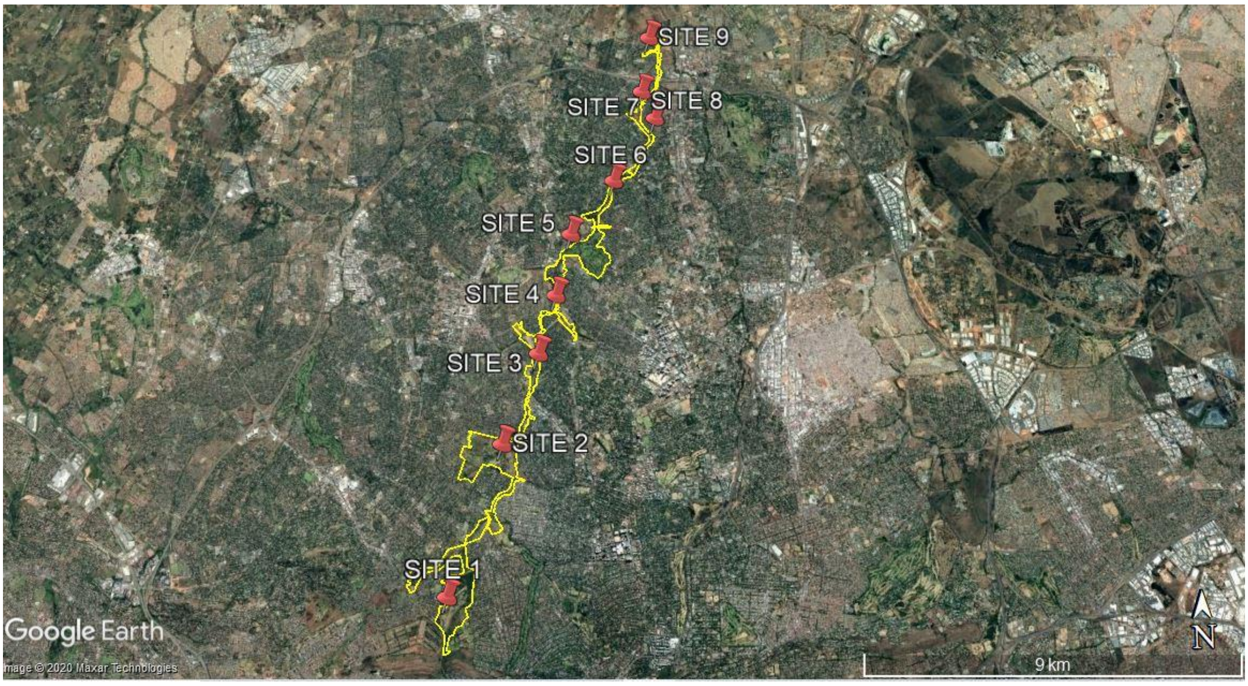

Figure 4: The Braamfonteinspruit ecological corridor, within Johannesburg, South Africa showing the midpoint of each quadrat within each study site (Google Earth Pro, 2020)

Site selection for the Modderfontein area was done differently due to limited site access. At a meeting with the Health, Safety and Environment manager for AECI Limited (the owners of the Modderfontein Nature Reserve as well as the surrounding land), I was given three coordinates, roughly two kilometres apart within the nature reserve as well as three coordinates in areas surrounding the reserve that I could have access to and that were relatively safe. I located each of these co-ordinates in the field and set up a 200 m^2 quadrat. In total, I set up six quadrats (Figure 5)

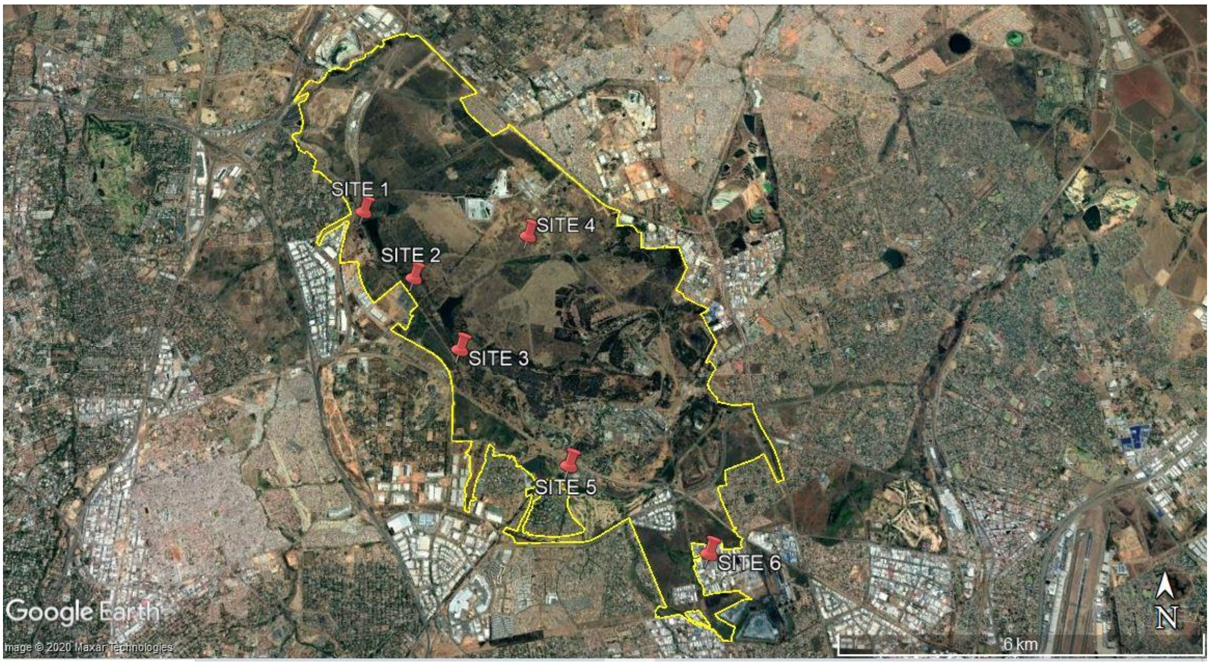

Figure 5: The Modderfontein ecological corridor, within Johannesburg, South Africa showing the midpoint of each quadrat within each study site (Google Earth Pro, 2020)

2.4 Vegetation Assessment

An assessment of vegetation structure, percentage ground cover, composition and species richness at every study site along each ecological corridor was completed during June, July and August 2019. In order to assess species composition, the Braun-Blanquet method was used (Braun-Blanquet, 1932; Table 3). This method involves taking representative samples of vegetation in an area. The Braun-Blanquet cover abundance scale was then used to assess the abundance of different species in the quadrat (Grobler *et al.,* 2002; Grobler *et al.,* 2006). Species were classed as either an herb (herbaceous plants), tree or grass. For the mean percentage ground cover of herbs, grass, trees and bare ground in each corridor, the Braun-Blanquet cover scores were converted into the midpoint percentage cover values: + = 0%; 1 = 2.5%; 2 = 15%; 3 = 37.5%; 4 = 62.5%; 5 = 87.5% (as per Vahdati *et al.,* 2017). All plant species within each quadrat were recorded and, where necessary, plant samples were collected and pressed for identification at the University of the Witwatersrand's Herbarium.

Table 3: Braun-Blanquet cover-abundance scale (Braun-Blanquet, 1932; Mueller-Dombois and Ellenberg, 1974)

Cover Score	Definition	Percentage Cover
5	Covers more than 3/4 of the reference area	>75
4	1/2 to 3/4 cover	50-75
3	1/4 to 1/2 cover	25-50
2	1/20 to 1/4 cover	5 to 25
1	Less than 1/20 cover	<5
+	None	0

Species richness in each quadrat along each ecological corridor was also determined. The number of different species present within the quadrats were added together to give an idea of total species richness within each corridor. Species diversity across all the sample quadrats was calculated using the Shannon-Wiener diversity index H':

$$H = -\sum P_i(\ln P_i)$$

where P_i = proportion of the species in the sample (Dingaan and Preez, 2017). Species evenness across the quadrats in each corridor was determined using Shannon's equitability:

$$E_H = {}^{H}/_{H_{max}} = {}^{H}/_{\ln S}$$

where S = total number of species. The median percentage cover data figures were used for these equations (as per Vahdati *et al.*, 2017). Lastly, grass biomass within each quadrat was intended to be measured using a pasture meter, however the grass was cut too short to be measured in both corridors.

2.5 Ecosystem Services

Three Urban Ecosystem Services were assessed in this study; flood regulation, temperature regulation and carbon sequestration. Gómez-Baggethun and Barton (2013) suggest that flood regulation and temperature regulation are vital services for increasing a city's adaptation capabilities and resilience to climate change. Furthermore, Els (2018) highlights these two services as well as carbon sequestration as being vital for reducing the impacts of climate change.

2.5.1 Flood regulation

Flood regulation in an ecosystem means that the ground is absorbing water and there is limited surface run-off. The elements in an ecosystem that allow for this are water bodies and groundwater sources that store water, vegetation that takes up water as well as soil that retains water and allows for water infiltration. The slope of land in the natural environment also has an impact on surface runoff. Specifically, a steep or flat slope increases or decreases surface runoff respectively. Lastly, the extent of impermeable surfaces in an environment determines the amount of surface runoff (Burkhard and Maes, 2017).

In order to assess flood regulation within the corridors, unconfined compressive strength (kg/cm^2) of the soil was measured using a pocket soil penetrometer during the dry season (June and July 2019). Unconfined compressive strength (kg/cm^2) provides a quantitative estimate of soil compaction (Amacher *et al*., 2004). Furthermore, soils that are compact will have a higher compressive strength than uncompact soils. Soils that are impermeable and highly compacted have reduced levels of water infiltration whereas a less compacted soil with macropores has better water drainage (Schüler, 2006). The end of the penetrometer was inserted into the top left, top right, bottom left, bottom right and middle point of each 200 m^2 quadrat. The readings on the penetrometer were recorded and the average reading of the site and each corridor was calculated (Braamfonteinspruit: n = 9; Modderfontein: n = 6). It should be noted that soil compression readings on the pocket penetrometer ranged from 0 kg/cm^2 to 5 kg/cm^2. Soils that have a mean soil compression strength of and above 4.4 kg/cm^2 were classed as compact (as per Amacher *et al.* 2004).Penetrometer readings took pace during the dry season and since readings differ between the wet and dry season, the results of these readings can only be an indication of soil compaction at the sites.

2.5.2 Temperature regulation

Methods for evaluating temperature regulation at each study site in the corridors was based on work by Shashua-Bar and Hoffman (2000) as well as Els (2018). At each study site within the two corridors, the temperature was recorded using a digital thermometer during September, October and November 2019. It must be noted that the temperature recording only took place on sunny days (as per Shashua-Bar and Hoffman, 2000). Temperature measurements were taken in shady areas under five trees that were closest to each quadrat (as per Els (2018)) located at each study site (Braamfonteinspruit: n = 45; Modderfontein: n = 30). The temperature was recorded once under each tree. In order to measure the cooling effect, a reference point about 50 to 100 m away from the shady area and in direct sunlight (not under trees) was chosen and the temperature at this point was also recorded using the same digital thermometer. The temperature difference between this point and the average temperature under the trees represents the cooling effect of the site (Shashua-Bar and Hoffman, 2000). Moreover,, outside each study site along both corridors, the average temperature under five trees (Braamfonteinspruit: n = 45; Modderfontein: n = 30) as well as the temperature at a reference point 50 to 100 m away from these trees and under direct sunlight was recorded and the cooling effect outside of the corridors was calculated. The cooling effect inside and outside the Braamfonteinspruit and Modderfontein ecological corridors was then compared. Lastly, the cooling effect inside the Braamfonteinspruit corridor was compared with the cooling effect inside the Modderfontein ecological corridor and the cooling effect outside both corridors was also compared.

2.5.3 Carbon sequestration

The carbon storage potential in each corridor was calculated using Lembani’s (2015) procedures. Five trees were randomly selected at each study site within the two corridors (Braamfonteinspruit: n = 45; Modderfontein: n = 30). A measuring tape (m) was used to measure the Circumference at Breast Height (1.3 m) (CBH) of each tree. The average CBH (cm) of trees within the two corridors was then calculated and used for further calculations. All measurements took place during September, October and December 2019.

The average Diameter (cm) at Breast Height (DBH) for each corridor was calculated using the equation

$$DBH = {}^{CBH}/_{\pi}$$

Furthermore, the average radius (r, in cm) of trees in both corridors was also calculated using the equation

$$r = {}^{DBH}\!/_{2}$$ (Lembani, 2015).

The Tietema (1993) allometric equation

$$Y = a(\pi r^2)^b$$

was used to calculate above-ground biomass (kg). The constant "a" is equal to 0.1936, the constant "b" is equal to 1.1654 and "r" refers to the radius of the tree stem (cm) ($r = {}^{DBH}\!/_{2}$) (Tietema, 1993). The stored carbon was worked out by converting the above ground biomass (Lembani, 2015) using a conversion factor 45 % (Martin and Thomas 2011; Thomas and Malczewski, 2007; Lembani, 2015), thus,

$$stored\ carbon = Y \times 45\%$$ (Els, 2018).

In order to calculate the total stored carbon of the entire ecological corridor, the total number of trees within the corridor was counted using Google Earth images and this number was then multiplied by the average stored carbon value of that particular corridor.

There are various different allometries to work out carbon sequestration. For this reason, carbon storage was again calculated using the Schäffler and Swilling's (2013) method as per Els (2018) in order to increase confidence in the results. The CBH of five trees within each study site in the corridors was measured as well as the height from ground level to the first branches (m). The percentage volume of the branches was estimated as a proportion of total tree volume (B). The branch volume, average tree circumference and stem length values were used to calculate DBH (CBH/π), Basal Area (π * DBH * DBH /40000), stem volume (BA * stem length * 0.7), total tree volume (stem volume/1-B), biomass (tree volume * 0.07) and average stored carbon (biomass * 45%) of each corridor. In order to calculate the total stored carbon (kg) within the ecological corridor, the average stored carbon value of one tree in the corridor was multiplied by the total number of trees found within the corridor. In order to determine confidence between these two carbon storage values, the percentage difference between both values was calculated.

2.6 Data Analysis

RStudio Version 1.2.5019 was used for all statistical data analyses and a Shapiro-Wilks test of normality was performed on all data sets before parametric or non-parametric analyses were performed. As the data was not normally distributed ($p>0.05$), Kruskal-Wallis tests were used to compare the percentage ground cover of herbs, grass, trees and bare ground within each corridor and a Mann-Whitney U test was performed to compare the percentage ground cover between the corridors.

The soil compaction at each site within the Braamfonteinspruit corridor was compared using a Kruskal-Wallis rank sum test as well as a multiple comparison test after Kruskal-Wallis (Kruskal-Wallis post-hoc test). The same tests were applied to the sites within the Modderfontein corridor. Furthermore, the soil compaction measurements within the Modderfontein nature reserve and outside of the nature reserve were compared using an unpaired two-sample Wilcoxon test. Lastly, the soil compaction measurements in the Braamfonteinspruit and Modderfontein ecological corridors were compared using a two-sample Wilcoxon test.

A Kruskal-Wallis test was used to compare the cooling effect inside and outside the Braamfonteinspruit corridor (not normal data, $p>0.05$) and a one-way ANOVA was used to compare the cooling effect inside and outside the Modderfontein ecological corridor (normal data, $p<0.05$). The cooling effect inside the two corridors (normal data, $p<0.05$) was compared using a one-way ANOVA and the cooling effect outside the two corridors (not normal data, $p<0.05$) was compared using a Kruskal-Wallis test.

For all statistical analyses, the significance level was set at $p<0.05$.

Chapter 3. RESULTS

3.1 Spatial analysis

The Braamfonteinspruit is made up of seventeen land-use types whilst the Modderfontein corridor consists of twenty different land use types (Table 4 & Table 5). Land-use within the Braamfonteinspruit ecological corridor is mostly made up of trees as well as planted and natural grasslands. Furthermore, industrial and residential (cluster) land-uses are least present within this corridor (Table 4). It should be noted that the total area of the Braamfonteinspruit is 5.22 km^2 The Modderfontein ecological corridor includes very little residential (cluster) and smallholding land uses and the most prominent land cover in this corridor is planted and natural grasslands followed by non-natural trees (Table 5). The Total area of the Modderfontein corridor was 39.2 km^2.

Table 4: Land use within the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa

Land-use	Braamfonteinspruit (Hectares)
Trees	298,28 (57,28%)
Planted & Natural grassland	101,07 (19,4%)
Open	41,39 (7,9%)
Golf Courses	38,50 (7,39%)
Wetlands	16,24 (3,12%)
Water	10,30 (1,98%)
Degraded natural vegetation	4,44 (0,85%)
Smallholdings	3,11 (0,6%)
School grounds	3,09 (0,59%)
Roads	2,04 (0,39%)
Residential	1,11 (0,21%)
Thicket, Bushland, Bush clumps	0,76 (0,15%)
Buildings	0,36 (0,07%)

Sports & Recreation	0,02 (0,005%)
Industrial	0,02 (0,004%)
Residential-cluster	0,02 (0,004%)

Table 5: Land use within the Modderfontein ecological corridor, within Johannesburg, South Africa

Land-use	**Modderfontein (Hectares)**
Planted & Natural grassland	1712,16 (43,06%)
Trees	1105,41 (27,08%)
Open	448,52 (11,28%)
Wetlands	196,58 (4,94%)
Mines & Quarries	103,16 (2,59%)
Cultivated, Commercial, Dryland/Rain fed	85,64 (2,15%)
Thicket, Bushland, Bush clumps	73,79 (1,86%)
Roads	66,86 (1,68%)
Industrial	48,62 (1,22%)
Water	44,30 (1,11%)
Degraded natural vegetation	28,00 (0,70%)
Golf Courses	20,97 (0,53%)
Rail	19,19 (0,48%)
Buildings	14,62 (0,37%)
Bare Rock & Soil (natural surfaces)	6,20 (0,16%)
Residential	1,00 (0,03%)
Sports & Recreation	0,86 (0,02%)
Residential-cluster	0,01 (0,0002%)
Smallholdings	0,004 (0,0001%)

Land cover with both corridors is mostly made up of low intensity land uses such as trees, grasslands and bare rock and soil. High intensity land uses such as residential, mines and roads make up a small percentage of land use within both corridors (Table 6, Figure 6, Figure 7, Figure 8 & Figure 9)

Table 6: Percentage of low and high intensity land use within the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

Ecological corridor	Percentage of low intensity land use	Percentage of high intensity land use
Braamfonteinspruit	90,73	9,27
Modderfontein	90,78	9,22

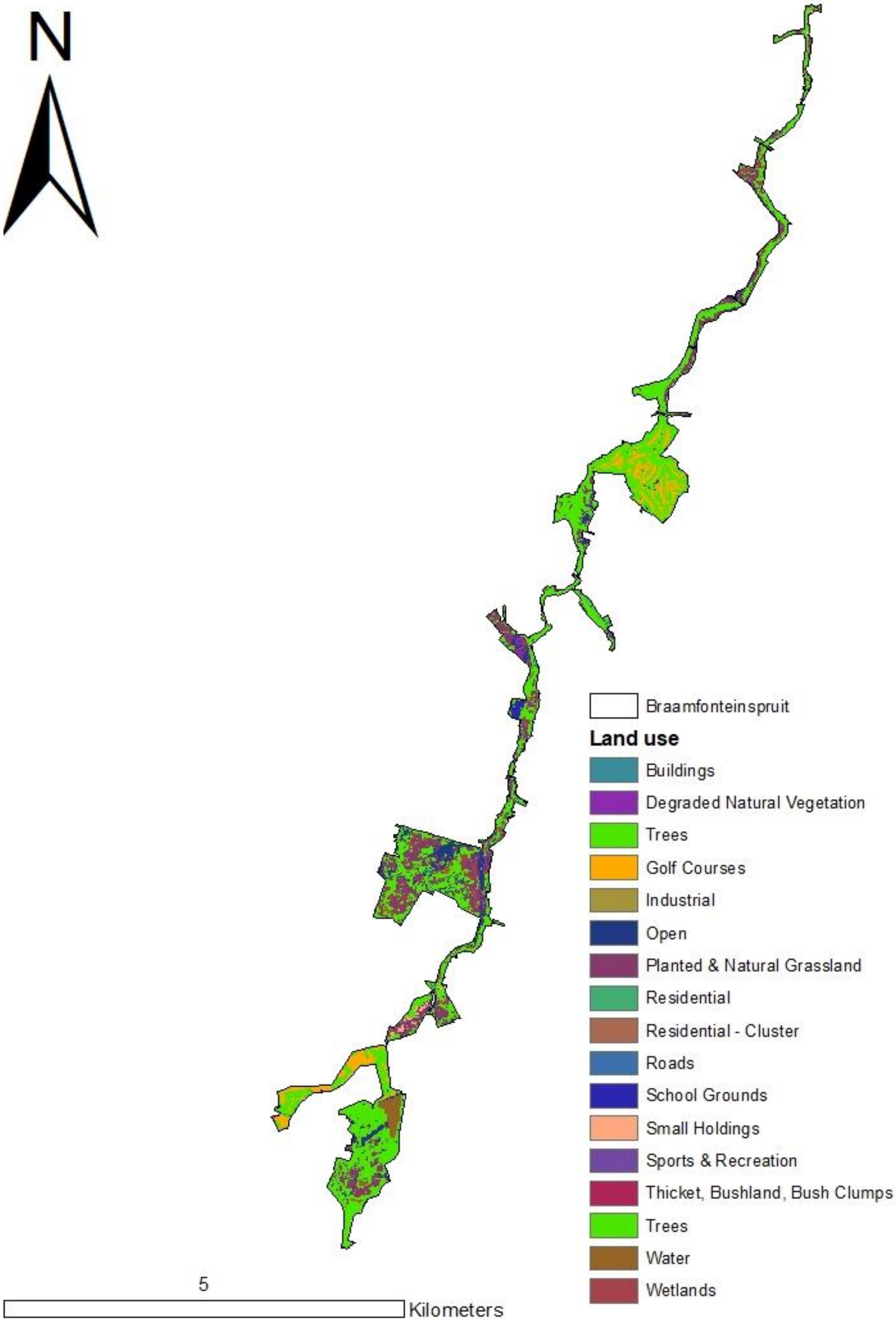

Figure 6: Land use within the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

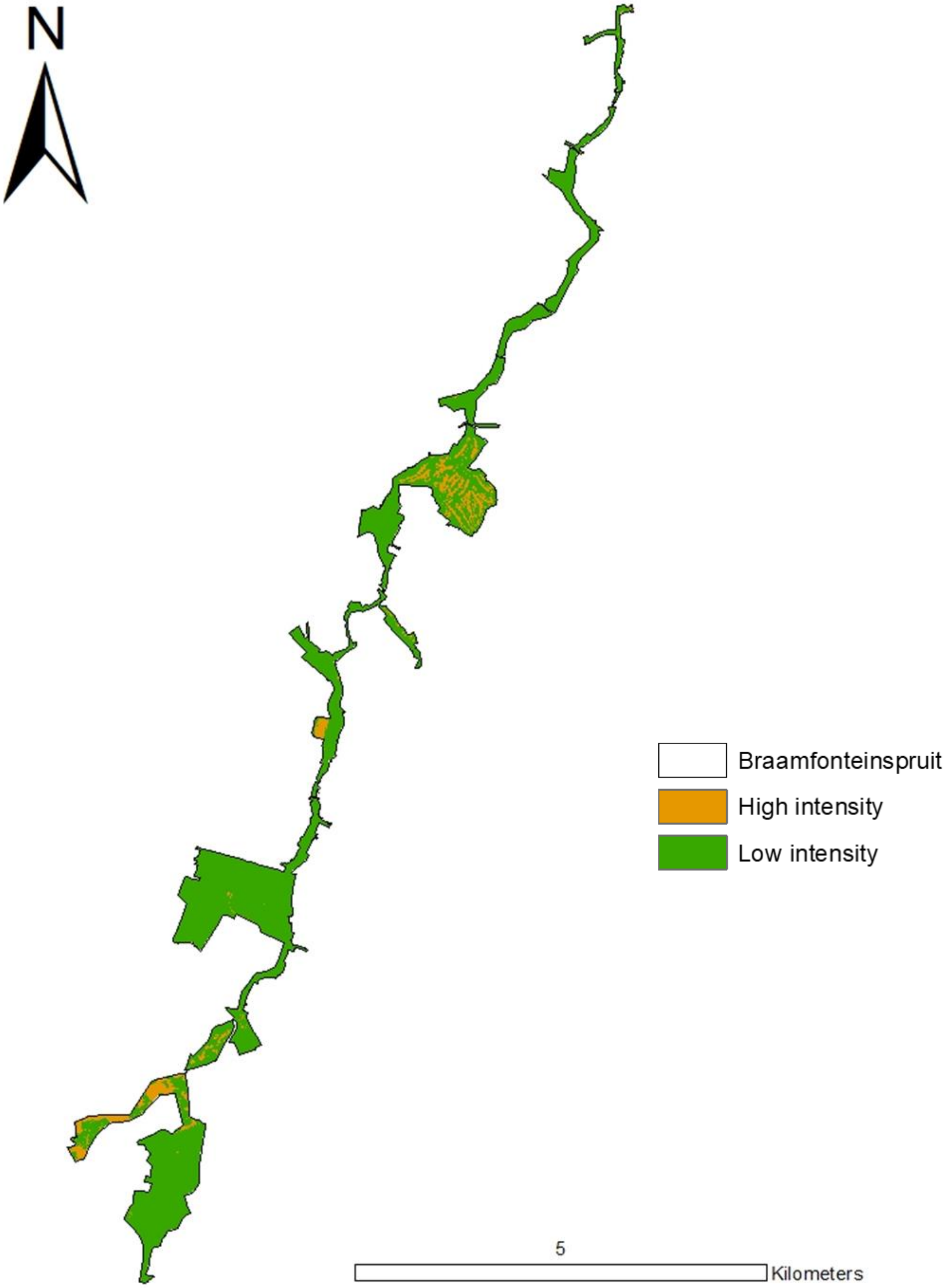

Figure 7: High and low intensity land use within the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

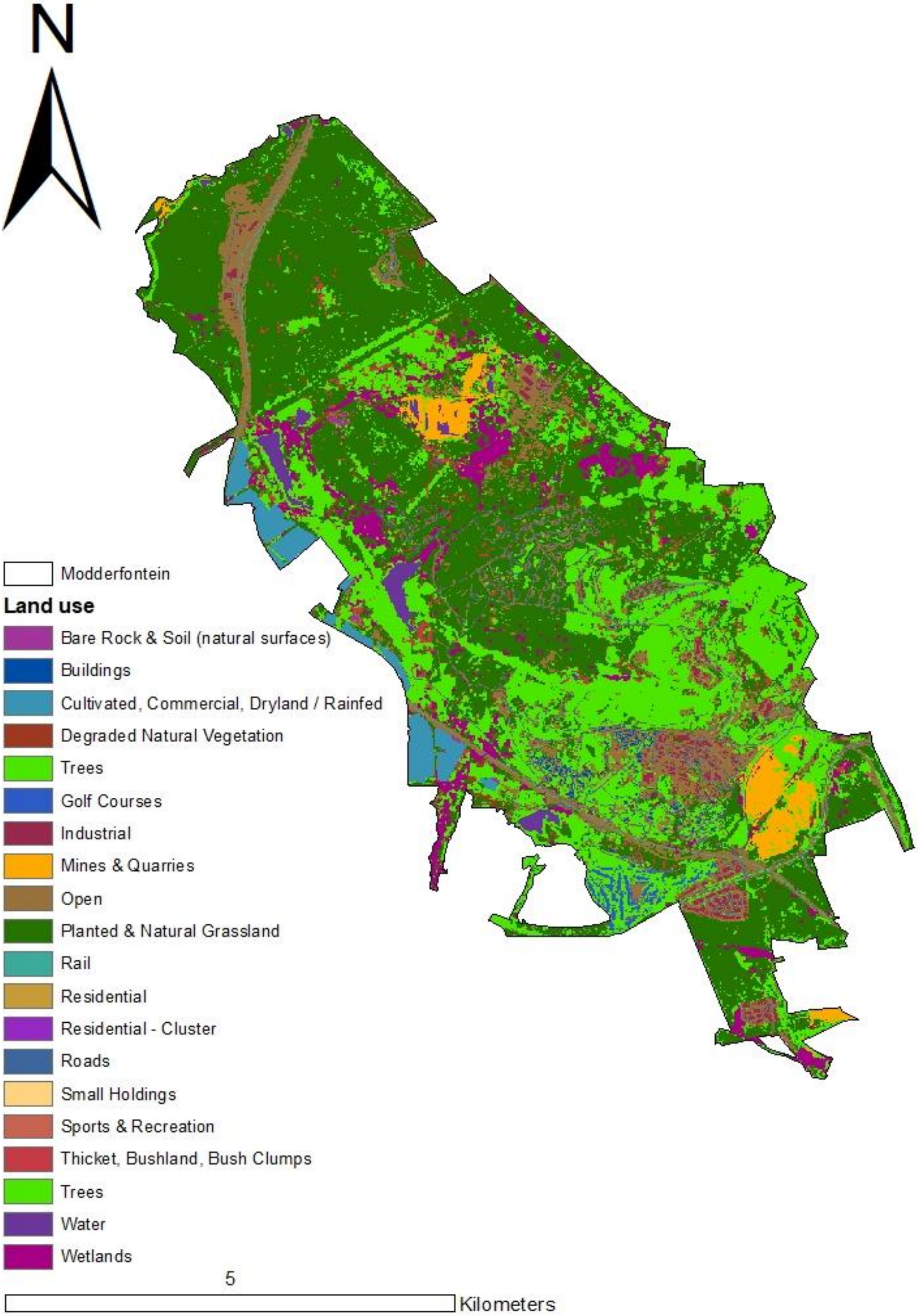

Figure 8: Land use within the Modderfontein ecological corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

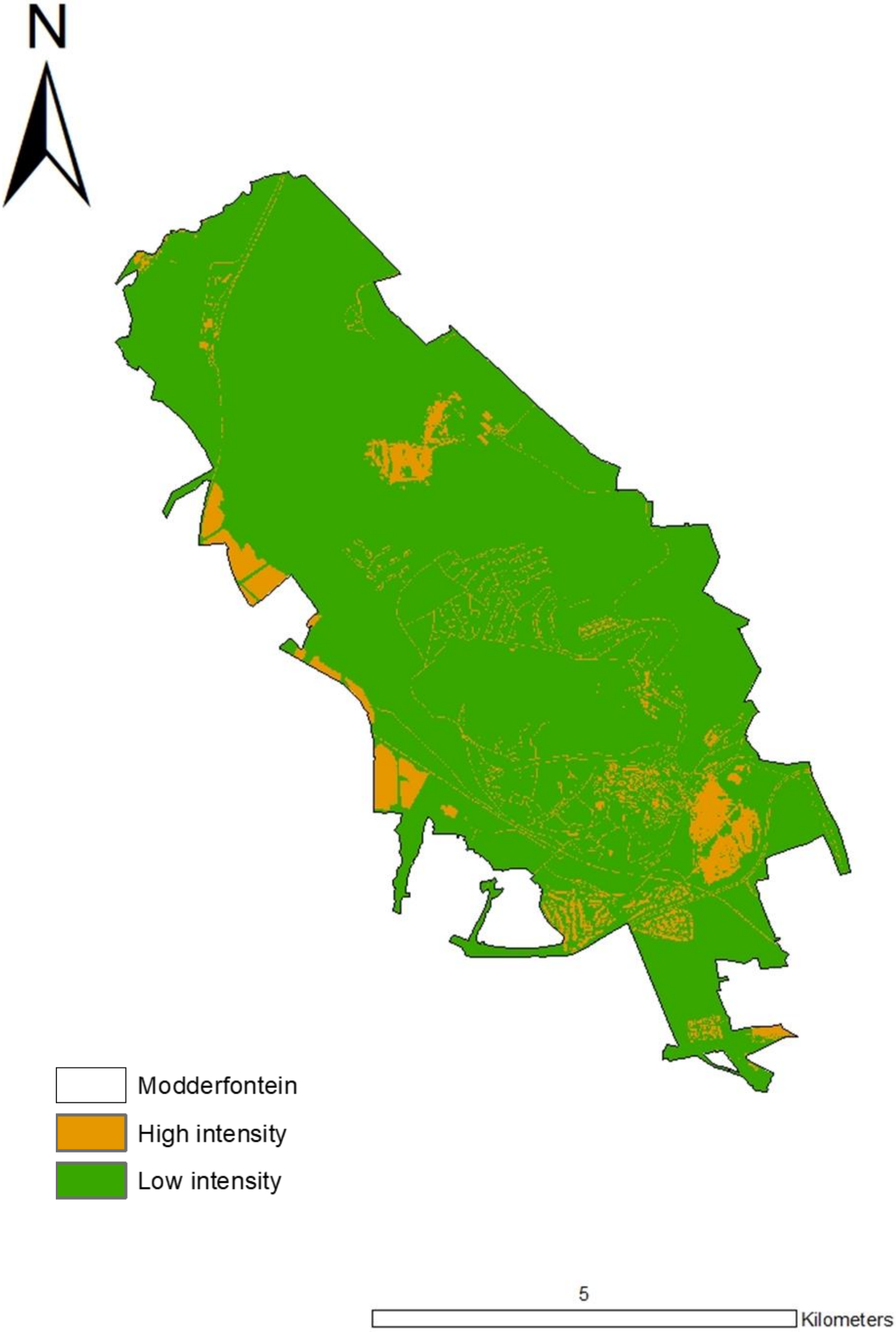

Figure 9: High and low intensity land use within the Modderfontein ecological corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

Seventeen different land uses surround the Braamfonteinspruit and Modderfontein ecological corridors. Land use surrounding the perimeter of the Braamfonteinspruit corridor is mainly made up of trees followed by residential areas (Table 7; Figure 10). The surrounding land that was assessed had a total area of 6.28 km^2. Whereas land use surrounding the Modderfontein corridor is mostly open space and then trees (Table 7; Figure 1). The surrounding land had a total area of 9.7 km^2. Thicket, bushland and bush clumps takes up the least amount of land cover surrounding the Braamfonteinspruit corridor (Table 7; Figure 10) and the Modderfontein corridor's surrounding land cover is least made up of golf-courses as well as thicket and bushland (Table 7; Figure 11).

Table 7: Land use surrounding the perimeter of the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

Land use	Braamfonteinspruit (Hectares)	Modderfontein (Hectares)
Buildings	11,34 (1,80%)	1,51 (0,15%)
Building (schools)	0,36 (0,06%)	-
School Grounds	5,94 (0,95%)	-
Sports & Recreation	9,40 (1,5%)	-
Golf Courses	2,69 (0,43%)	0,24 (0,02%)
Industrial	0,54 (0,09%)	46,38 (4,74%)
Residential - Cluster	38,82 (6,18%)	8,53 (0,87%)
Residential	93,91 (14,95%)	30,81 (3,14%)
Small Holdings	0,59 (0,09%)	35,81 (3,66%)
Roads	63,12 (10,05%)	51,47 (5,26%)
Thicket, Bushland, Bush Clumps	0,02 (0,004%)	2,46 (0,25%)
Trees	286,87 (45,68%)	174,87 (17,88%)
Planted & Natural Grassland	26,14 (4,16%)	175,65 (17,96%)
Wetlands	0,25 (0,04%)	12,72 (1,3%)

Degraded Natural Vegetation	0,71 (0,11%)	0,61 (0,06%)
Open	86,47 (13,77%)	227,04 (23,22%)
Water	-	3,50 (0,36%)
Bare Rock & Soil (natural surfaces)	0,93 (0,15%)	0,09 (0,009%)
Township Formal	-	18,23 (1,86%)
Rail	-	1,83 (0,19%)
Cultivated, Commercial, Dryland / Rainfed	-	77,44 (7,92%)
Mines & Quarries	-	108,79 (11,12%)

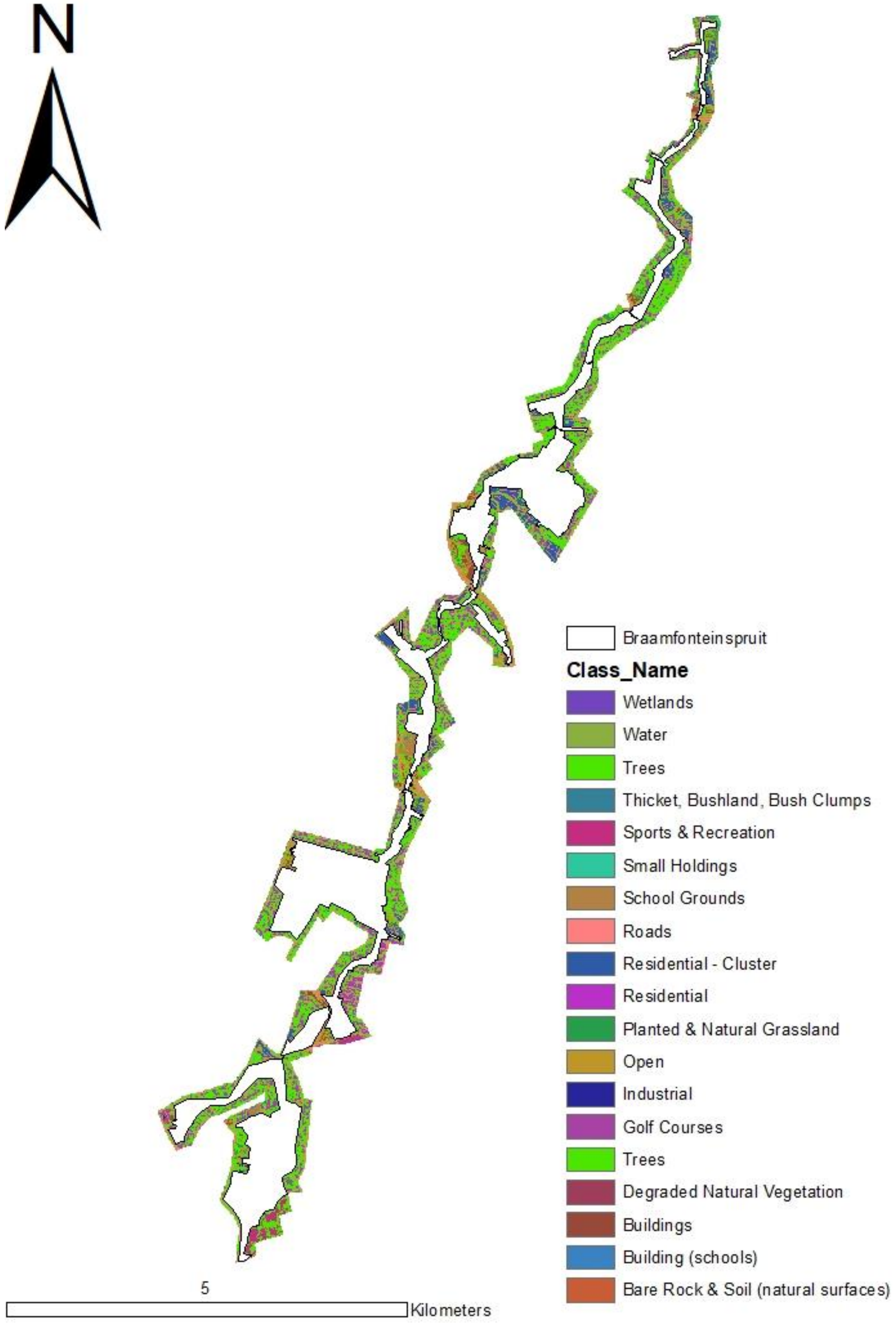

Figure 10: Land use surrounding the perimeter of the Braamfonteinspruit corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

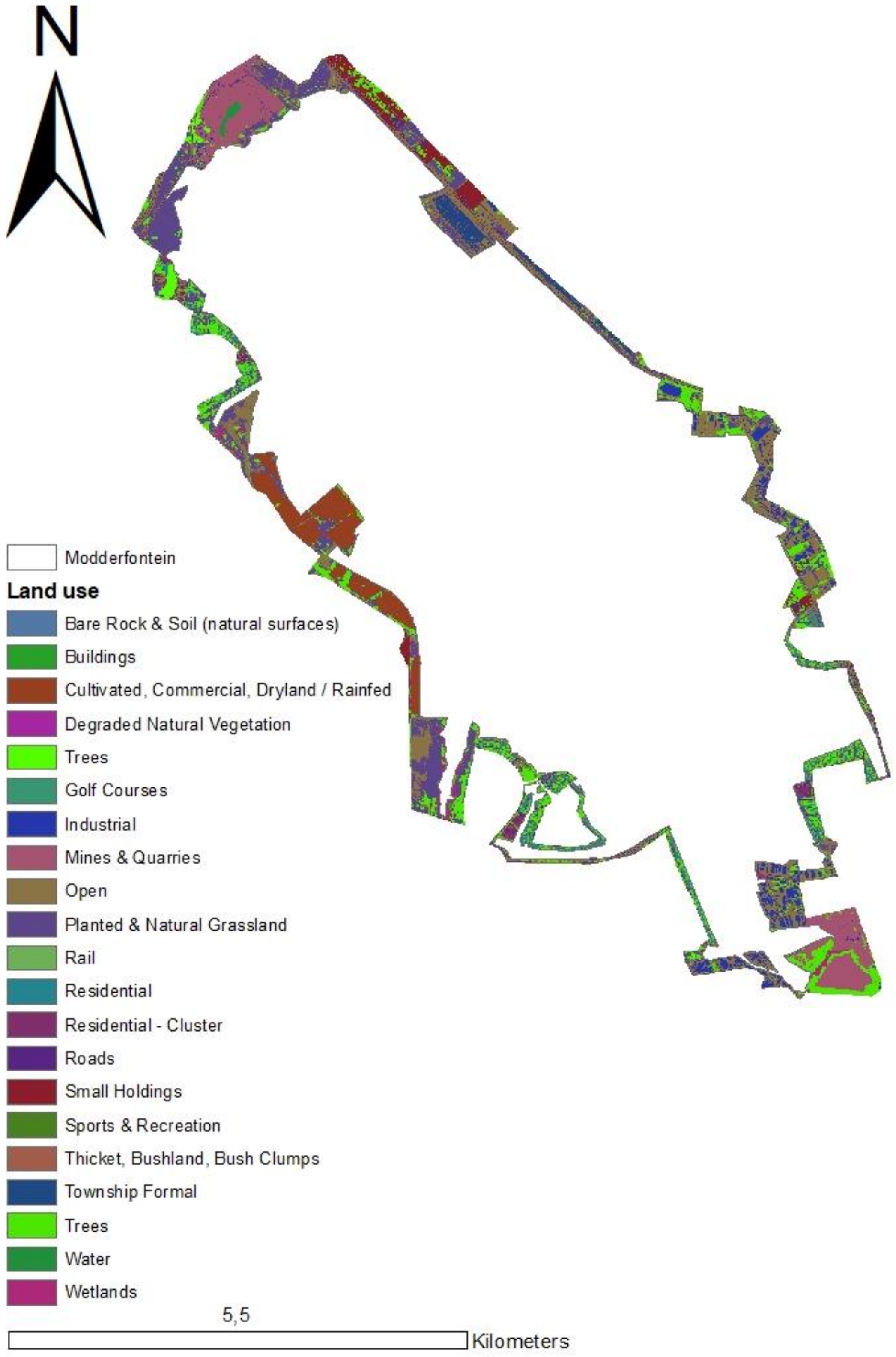

Figure 11: High and low intensity land use surrounding the perimeter of the Modderfontein ecological corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

The percentage of high intensity land uses surrounding both corridors is higher than it is within the corridors. However, the majority of land use along the perimeter of the corridors is mostly covered with low intensity land uses such as grasslands and trees and least covered in high intensity land uses such as industrial and buildings (Table 8; Figure 12 & Figure 13).

Table 8: Percentage of low and high intensity land use surrounding the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

Ecological corridor	Percentage of low intensity land use	Percentage of high intensity land use
Braamfonteinspruit	63.91	36.09
Modderfontein	61.04	38.96

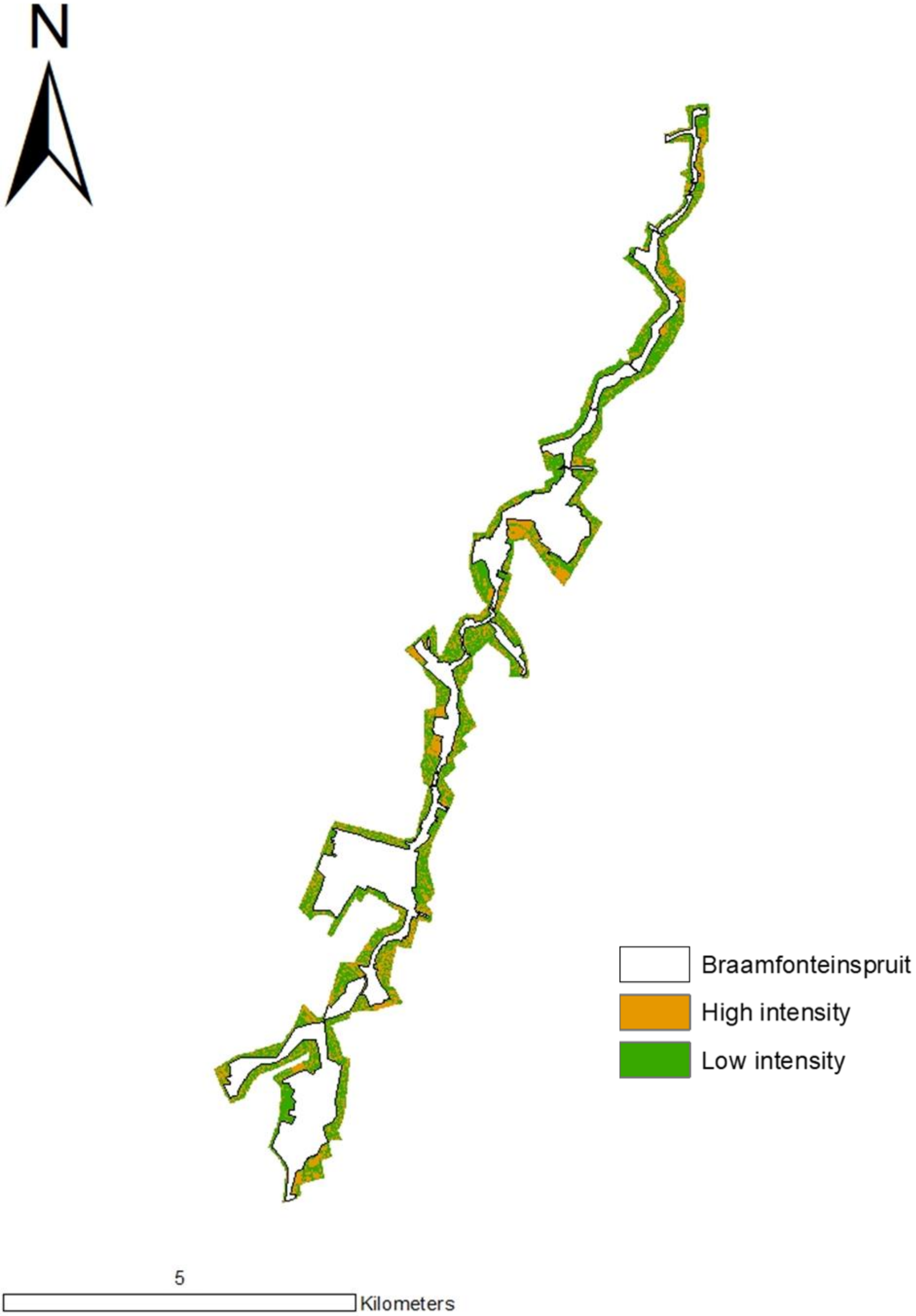

Figure 12: High and low intensity land use surrounding the perimeter of the Braamfonteinspruit corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

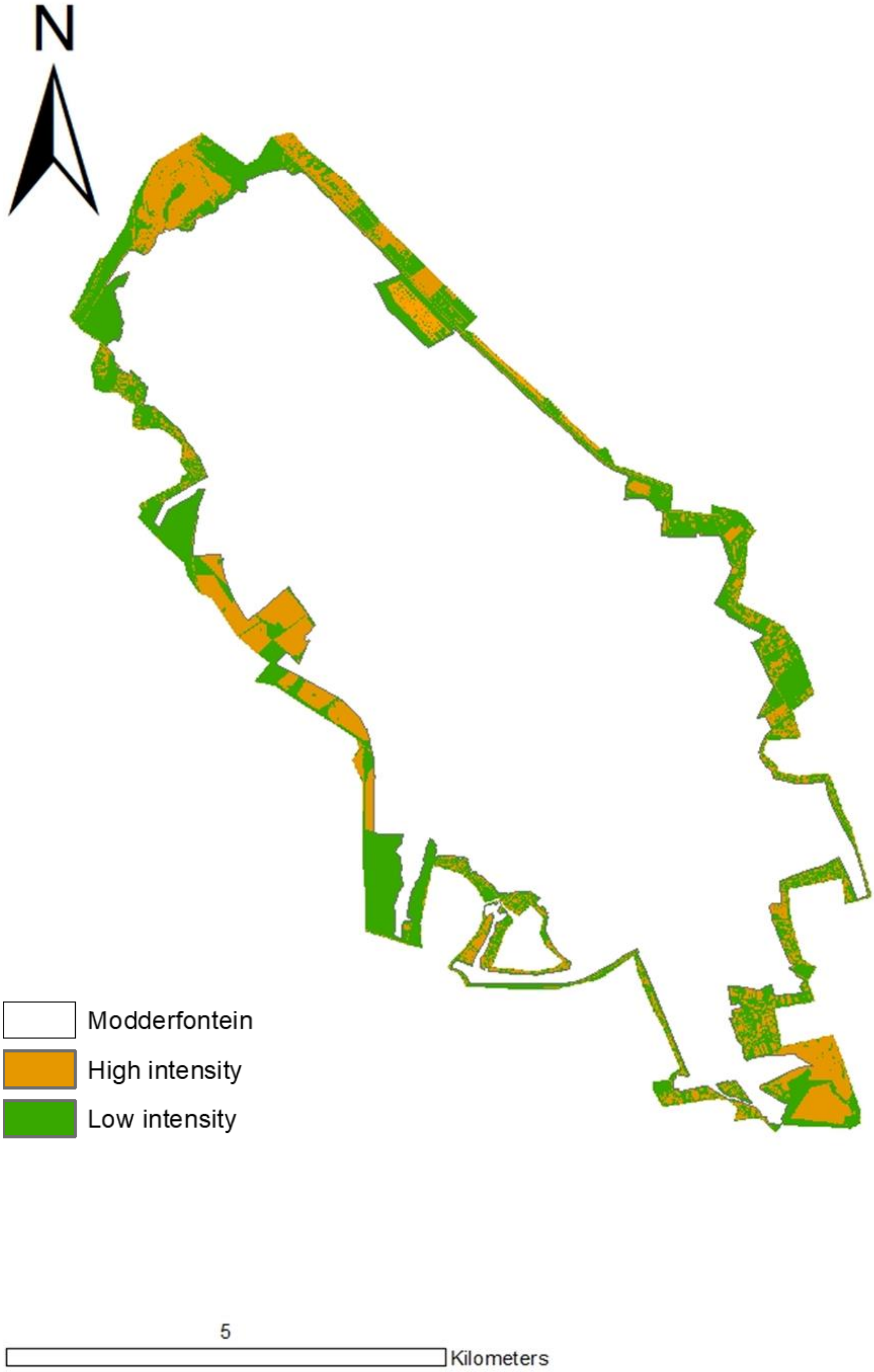

Figure 13: High and low intensity land use surrounding the perimeter of the Modderfontein ecological corridor, within Johannesburg, South Africa (©GEOTERRAIMAGE – Land cover/use 2.5m 2014)

There were no Protected Areas (PAs) found within the Braamfonteinspruit ecological corridor, however there were two PAs within 1 km of the corridor that are both municipal nature reserves, namely Melville Koppies and Rietfontein ridge. Thirteen sensitive sites were identified within and/or intersecting the corridor that were all classified as important sites by GDARD's C-Plan. There were 20 sites within 1km of the corridor of which 18 were classified as important sites in the C-Plan, one as an irreplaceable site and one as a reserved site (Figure 14).

According to the C-Plan there were no PAs or conservancies in or within 1km of the Modderfontein ecological corridor, however there were 31 sensitive sites within the corridor, 18 being classified as important sites and 13 being irreplaceable sites. Furthermore, 46 sensitive sites were 1 km around the ecological corridor; 26 of the sites being important and 20 of the sites being classified by the C Plan as irreplaceable (Figure 15).

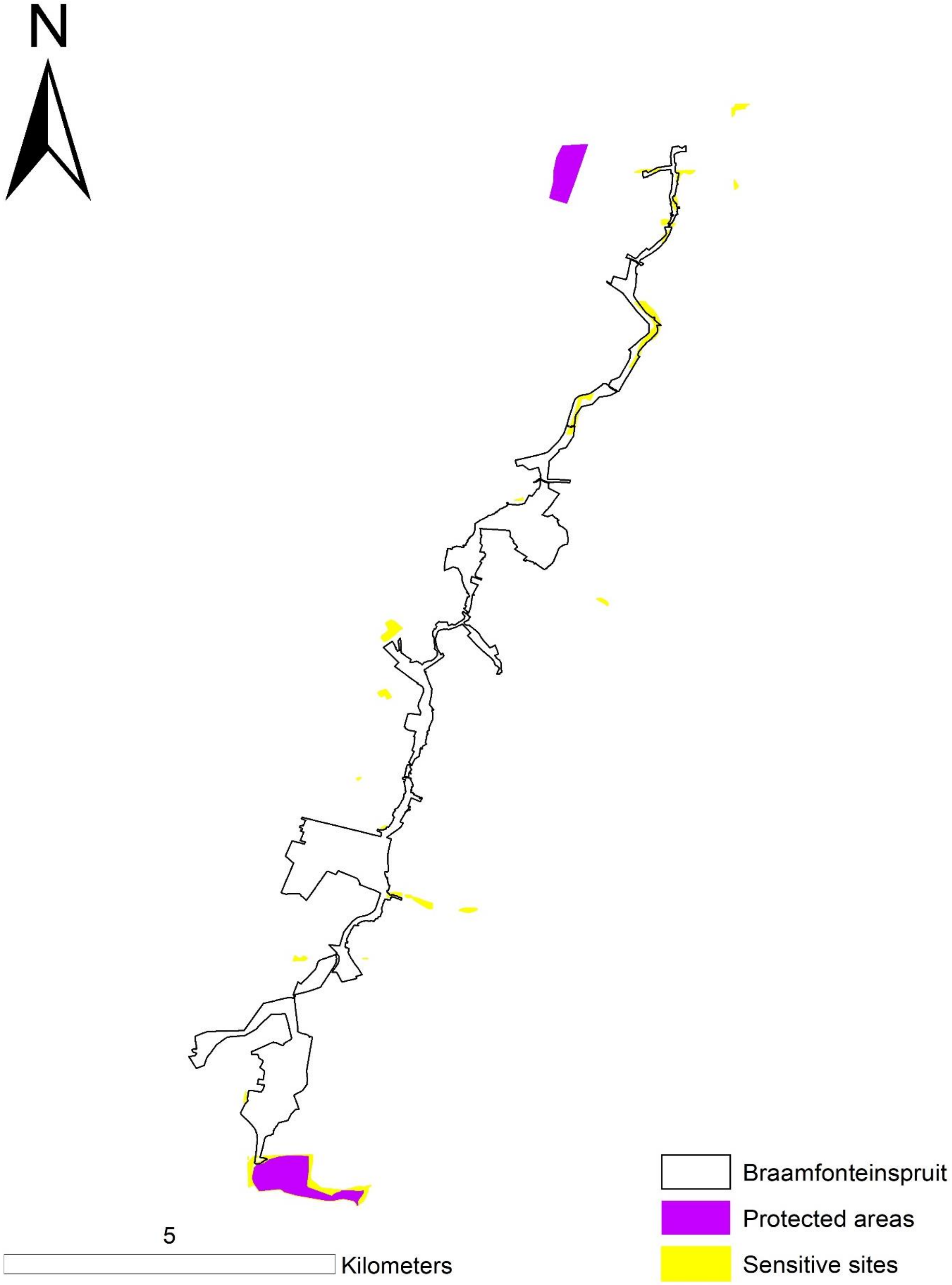

Figure 14: Protected Areas and sensitive sites within and 1km surrounding the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa (GDARD, 2013)

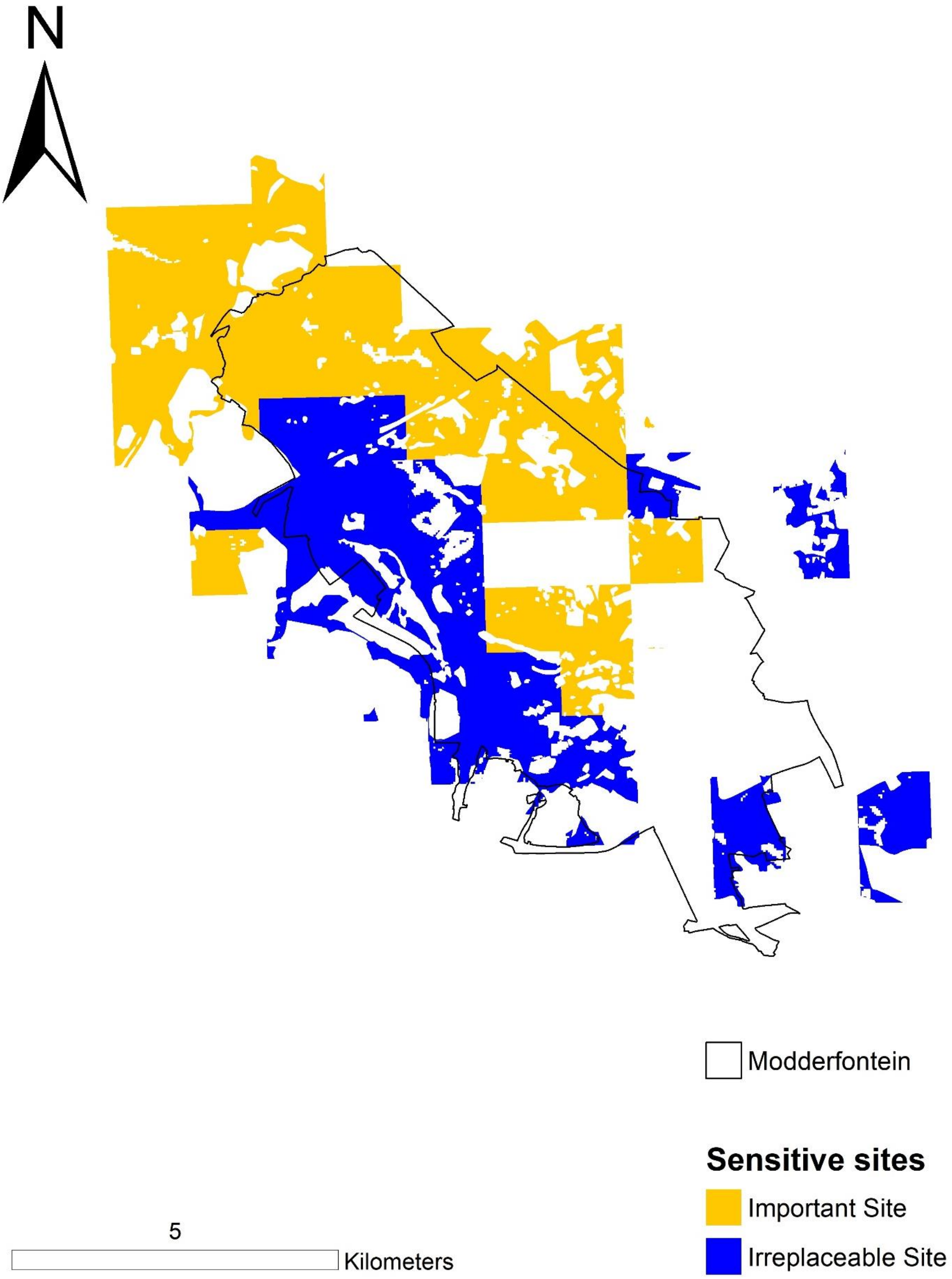

Figure 15: **Sensitive sites within and 1km surrounding the Modderfontein ecological corridor, within Johannesburg, South Africa (GDARD, 2013)**

Thirty-three single non-perennial rivers were identified within and intersecting the Braamfonteinspruit corridor. Additionally, 18 single non-perennial rivers were found 1 km around this corridor. Five ridges were completely within and intersecting the Braamfonteinspruit; four of them being class 4 ridges and one being a class 2 ridge. There were nine ridges 1 km around the corridor; two being class 2 ridges, six being class 4 ridges and 1 being a class 3 ridge (Figure 16). According to the C-Plan there were no wetlands within the Braamfonteinspruit or 1km surrounding it, however according to GCRO there were wetlands present within and around the corridor.

There were 92 rivers within and intersecting the Modderfontein ecological corridor; one being a single perennial river and ninety-one being single non perennial rivers. There were thirty-seven single non perennial rivers found within 1 km from the corridor. Lastly, there were no ridges found within 1km from the ecological corridor, however seven ridges were within or intersecting the corridor; two being Class 2 ridges, one being a Class 4 ridge and four being Class 3 ridges (Figure 17). It should be noted that the C-Plan identified no wetlands within or 1 km around the corridor, however GCRO does identify wetlands within and around the Modderfontein ecological corridor.

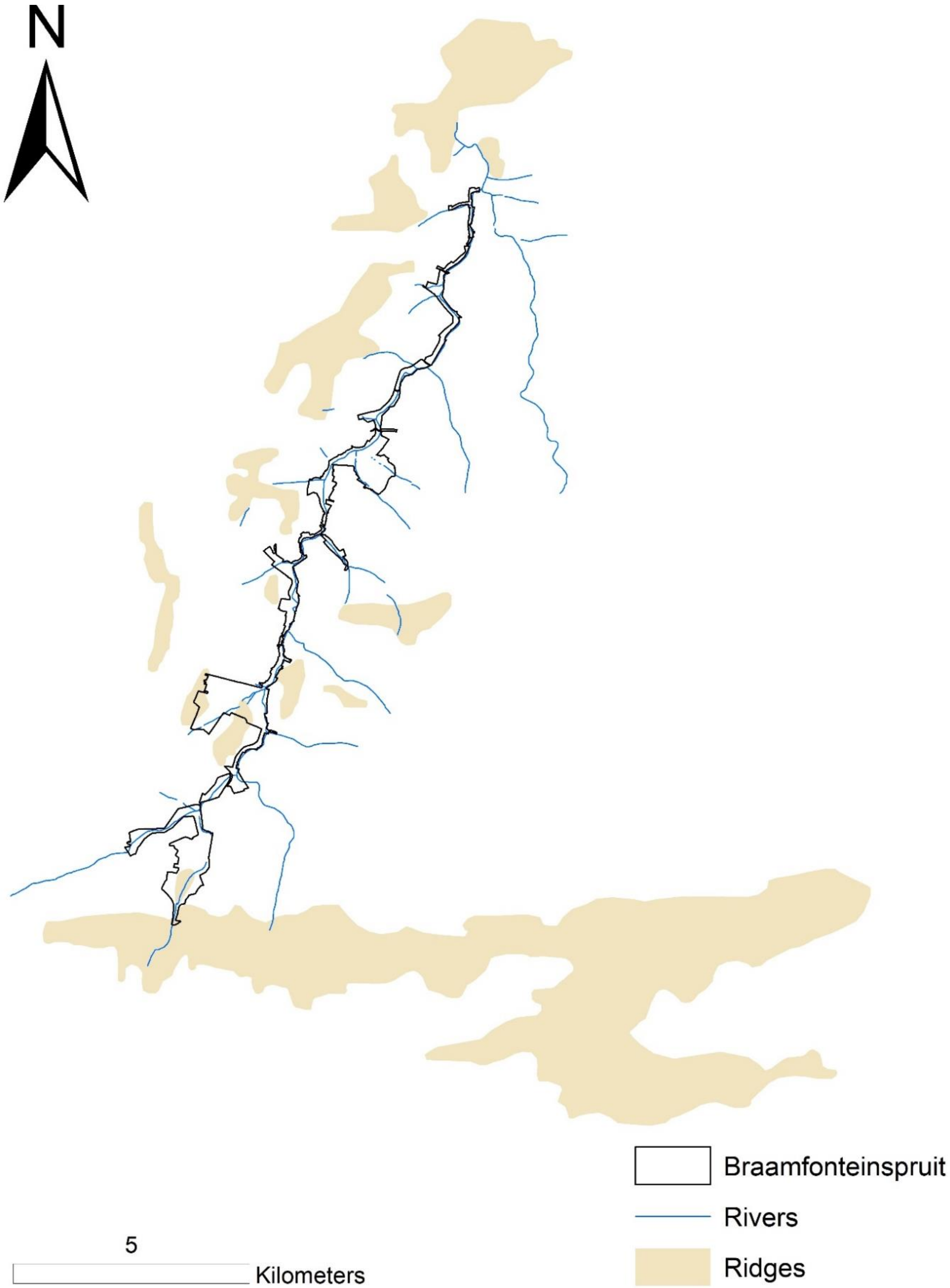

Figure 16: Rivers and ridges within, intersecting and 1km around the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa (GDARD, 2013)

Figure 17: Rivers and ridges within and 1km surrounding the Modderfontein ecological corridor, within Johannesburg, South Africa (GDARD, 2013)

3.2 Vegetation analysis

Various species of herbs, grass and trees were found within each study site and corridor (Appendix). Overall, the Braamfonteinspruit corridor had the highest species richness with thirty-five different species recorded whilst the Modderfontein corridor had twenty-five different species. The majority of the quadrats within the Braamfonteinspruit and Modderfontein corridors had the highest species richness of herbs (Table 9; Figure 18 & Figure 19). Both corridors had a higher percentage of exotic than native species (Table 10). Moreover, species diversity (H) and species evenness (E_H) were lower in the Braamfonteinspruit corridor (H= 1.16211, E_{H} = 0.32686) than in the Modderfontein corridor (H= 1.9253, E_{H} = 0.5981).

Table 9: The percentage of herb, grass and tree species in the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

Ecological corridor	**Braamfonteinspruit**	**Modderfontein**
Herb (%)	80	64
Grass (%)	9	12
Tree (%)	11	24

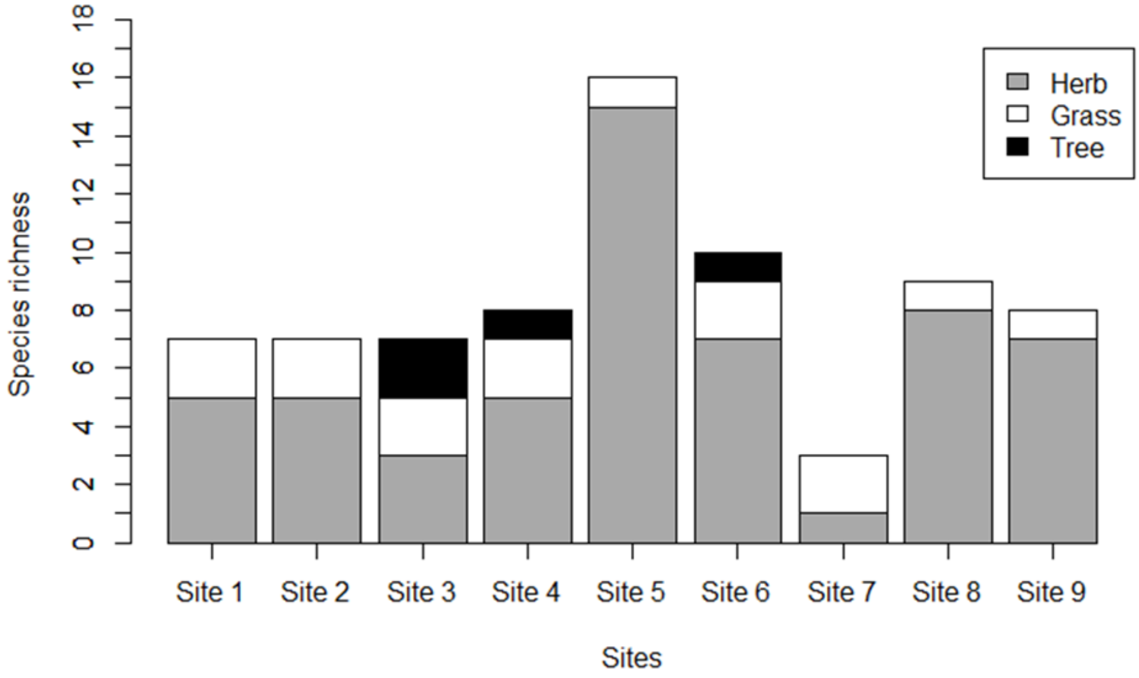

Figure 18: Species richness in quadrats at different sites along the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa

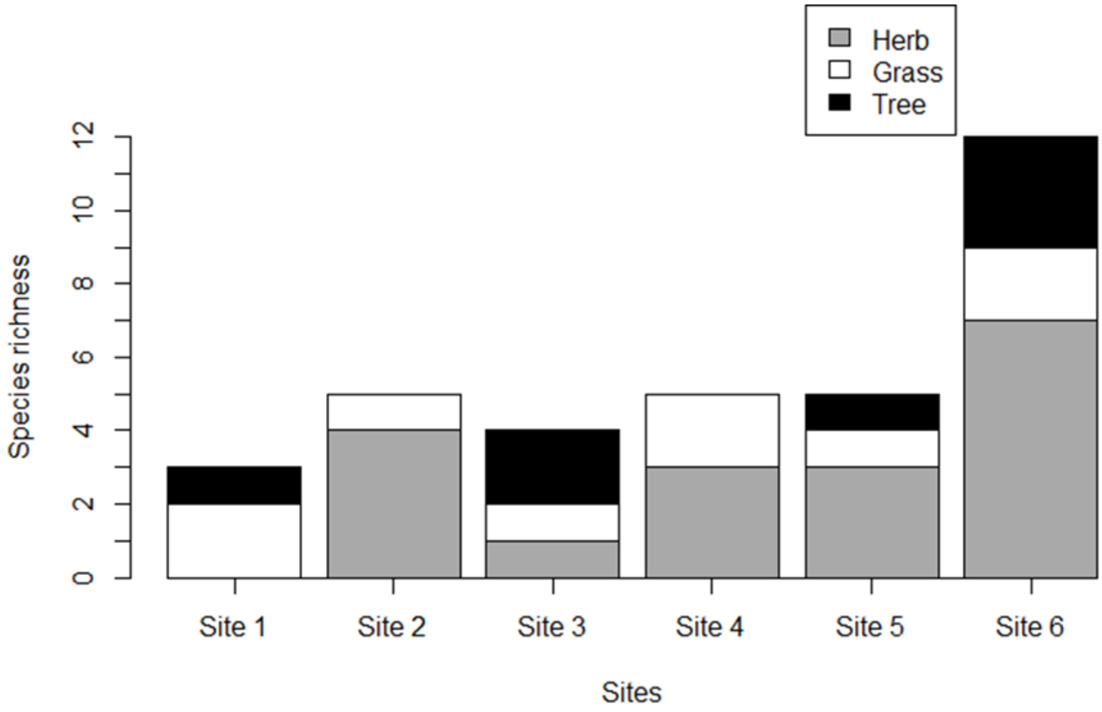

Figure 19: Species richness in quadrats at different sites along the Modderfontein ecological corridor, within Johannesburg, South Africa

Table 10: The percentage of exotic and native species in the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

Ecological corridor	Exotic species (%)	Native species (%)
Braamfonteinspruit	87	13
Modderfontein	88	12

Ribwort plantain (*Plantago lanceolata)* and Cats eye (*Hypochaeris radicata*) were the most widespread herb species in the Braamfonteinspruit corridor, while Tassel three-awn (*Aristida congesta*) and Kikuyu grass (*Pennisetum clandestinum)* were the most widespread grass species in the Braamfonteinspruit corridor. Blackjack (*Bidens pilosa*) and Tall verbena (*Verbena bonariensis*) were the most widespread herbs in the Modderfontein ecological corridor, with Kikuyu grass (*Pennisetum clandestinum)* being the most widespread grass species in the Modderfontein ecological corridor.

The quadrates sampled in both corridors were mostly covered with grass. Herbaceous plants were the second highest ground cover for quadrats in both corridors followed by bare ground and then trees (Figure 20). Furthermore, the grass, herb and bare ground Braun-Blanquet cover scores for both corridors were the same except for trees where the Braamfonteinspruit corridor had a higher cover score for trees than the Modderfontein ecological corridor (Table 11). There was a significant difference between the herb, grass, tree and bare ground cover in the Braamfonteinspruit corridor (x^2 = 36.965, $p < 0.001$). According to the post-hoc test, the significant difference is specifically between herbs and grass (obs.dif = 36.44; critical.dif =18.15), grass and bare ground (obs.dif = 39.66; critical.dif = 30.02) as well as grass and tree ground cover (obs.dif = 40.82; critical.dif = 37.26). There was a significant difference between the ground cover of herbs, grass, trees and bare ground in the Modderfontein corridor (x^2 = 16.406, $p < 0.001$). According to the post-hoc test, the significant difference is particularly between herbs and grass (obs.dif =12; critical.dif =11.35) as well as grass and trees (obs.dif = 18.89; critical.dif =14.01). It should be noted that there were only two sites with bare ground cover in the Modderfontein corridor, thus these data points have been excluded from the post hoc analysis (Figure 20).

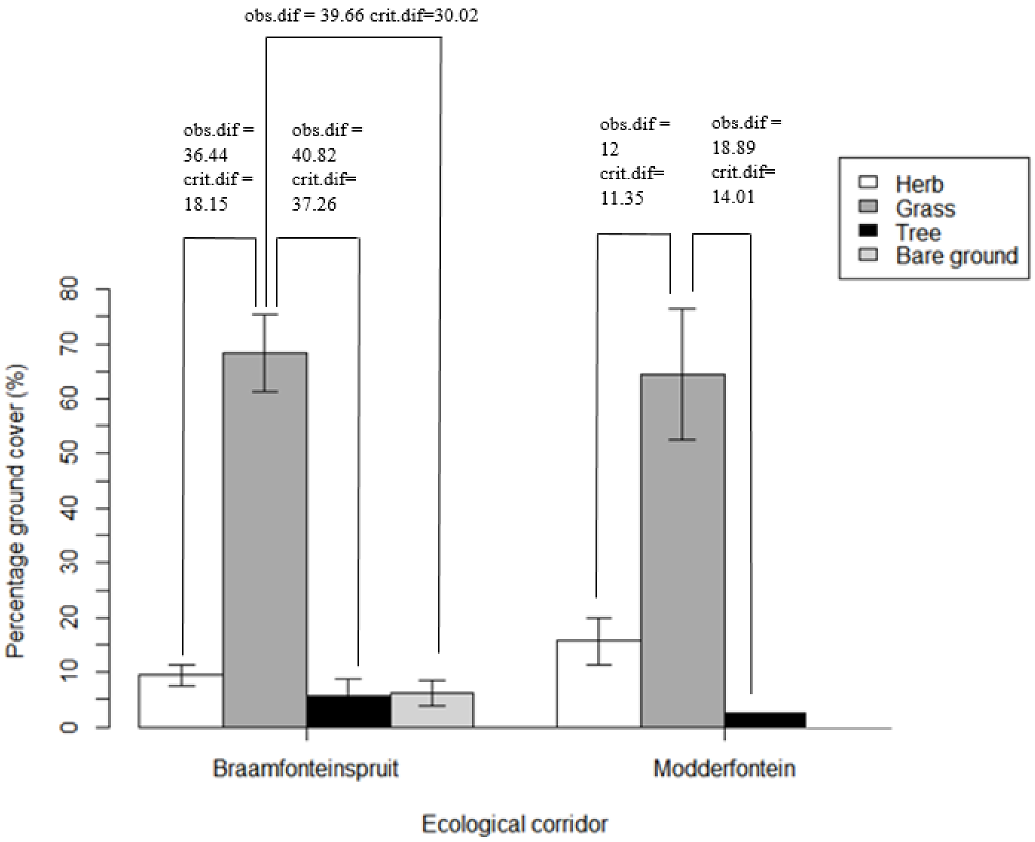

Figure 20: Percentage ground cover of the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

Table 11: The average Braun-Blanquet cover scores of herbs, grasses, trees and bare ground within the Braamfonteinspruit and Modderfontein ecological corridors

Ecological Corridor	Herb	Grass	Tree	Bare ground
Braamfonteinspruit	2	4	2	2
Modderfontein	2	4	1	2

3.3 Ecosystem services

3.3.1 Flood regulation

The average soil compaction measurement of the Braamfonteinspruit corridor was relatively low at 2.67 kg/m^2. There was a significant difference between the different sites' soil compaction measurements ($x^2 = 30.336$, p = 0.0001843). According to the post-hoc test, the significant difference in soil compaction was specifically between Sites 2 and 6 (obs.dif = 27.65; critical.dif =27.55), Sites 1 and 3 (obs.dif = 28; critical.dif =27.55), Sites 1 and 6 (obs.dif = 35.0; critical.dif =27.55) (Figure 21).

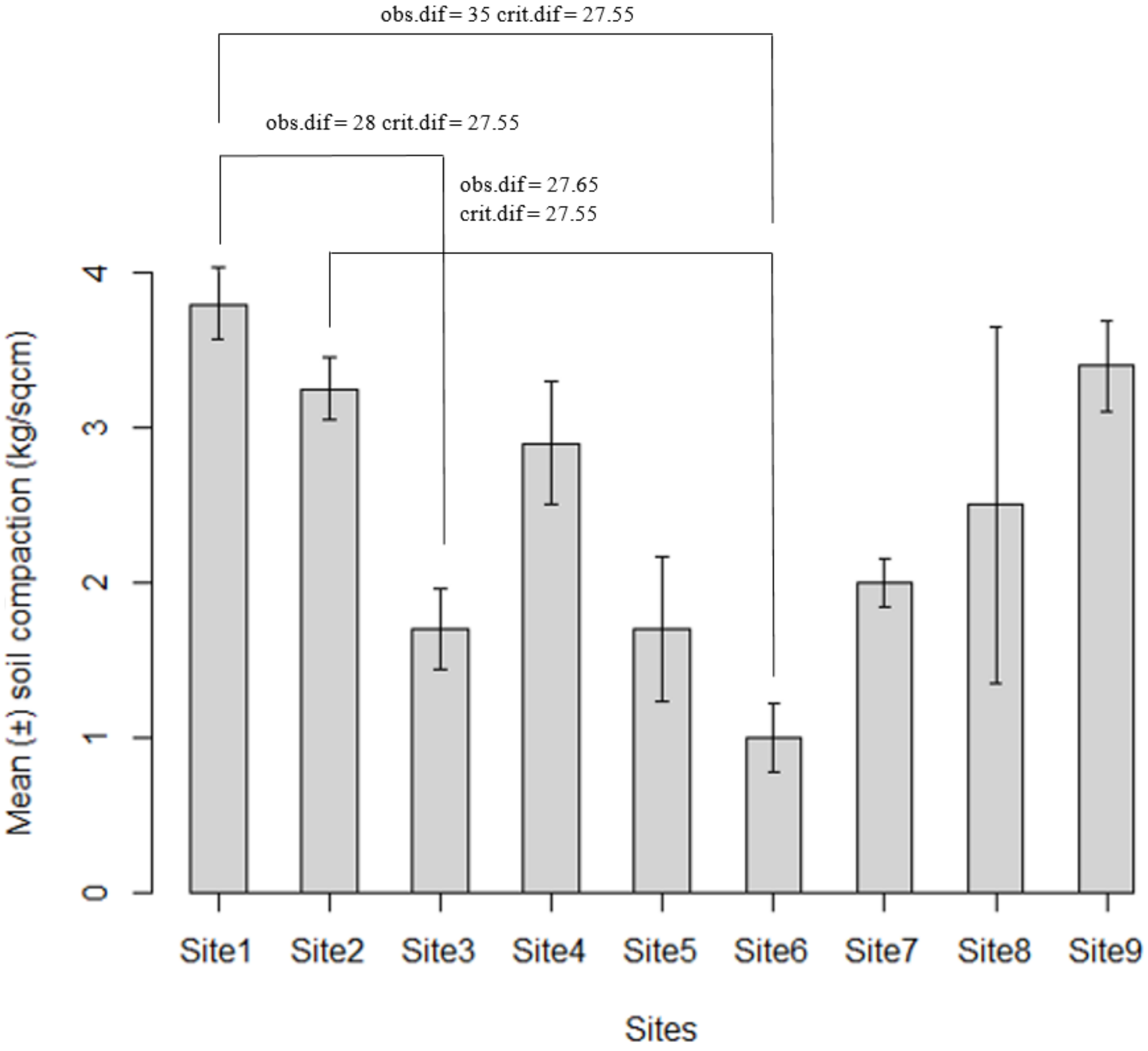

Figure 21: Mean (±SE) soil compaction (kg/cm^2) within the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa

The Modderfontein ecological corridor had a mean soil compaction measurement of 2.32 kg/cm^2 and there was a significant difference between the soil compaction values of the six sites ($x^2 = 22.759$, $p = 0.0003752$). The post-hoc test identified a significant difference specifically between Sites 2 and 4 (obs.dif = 16.8; critical.dif =16.34) as well as Site 2 and 5 (obs.dif = 18.4; critical.dif =16.34) (Figure 22).

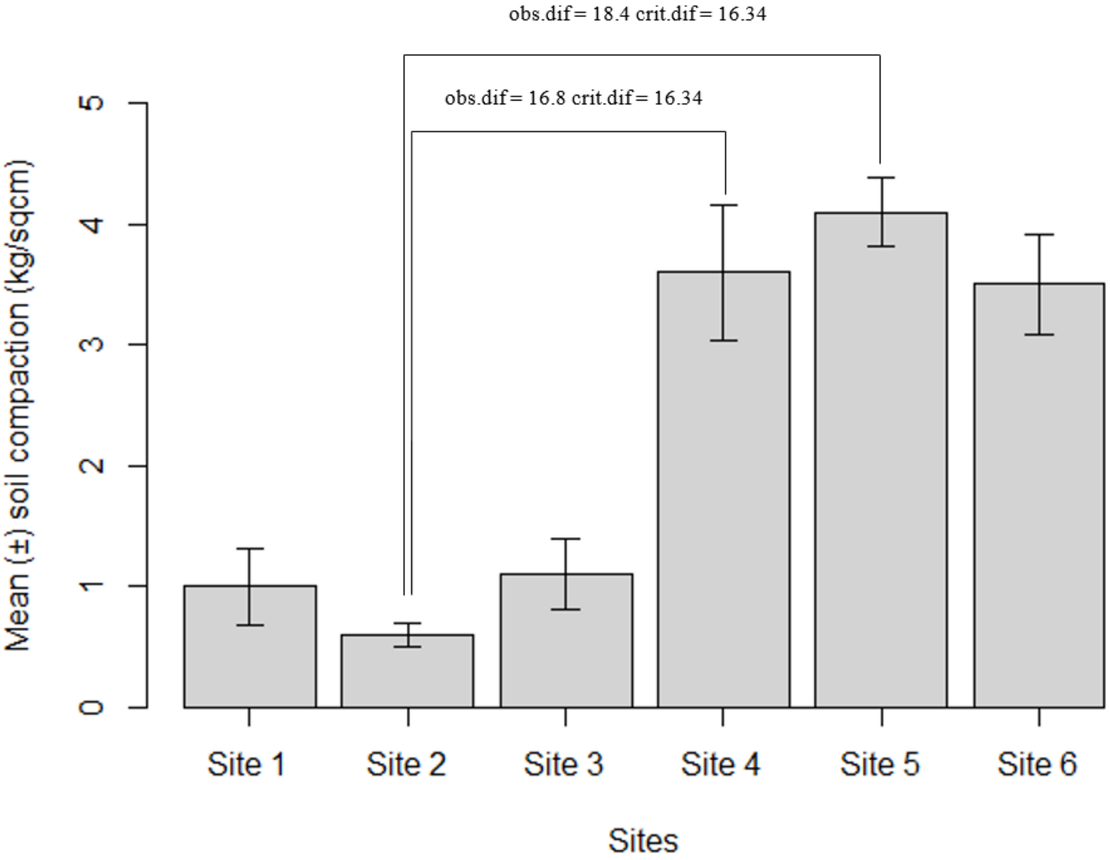

Figure 22: Mean (±SE) soil compaction (kg/ cm^2) within the Modderfontein ecological corridor, within Johannesburg, South Africa

Site 1, Site 2 and Site 3 fell within the Modderfontein Nature Reserve, whereas Site 4, Site 5 and Site 6 fell outside the reserve. There was a significant difference ($W = 2$, $p = 0.000003129$) between the soil compaction measurements within the Modderfontein Nature Reserve and outside the reserve (Figure 23). Furthermore, there was no significant difference in the soil compaction (kg/cm2) measurements between the two ecological corridors (W= 922.5, p= 0.2916) (Figure 24).

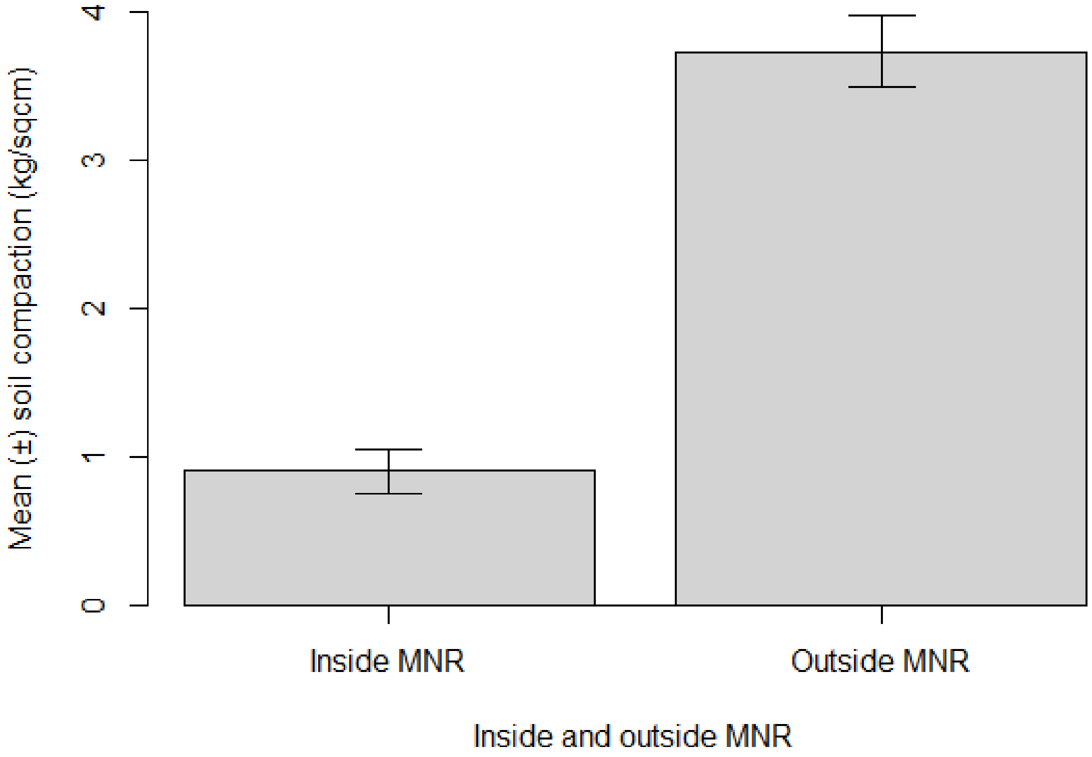

Figure 23: Mean (±SE) soil compaction (kg/cm^2) inside and outside the Modderfontein Nature Reserve (MNR); the Modderfontein ecological corridor, within Johannesburg, South Africa

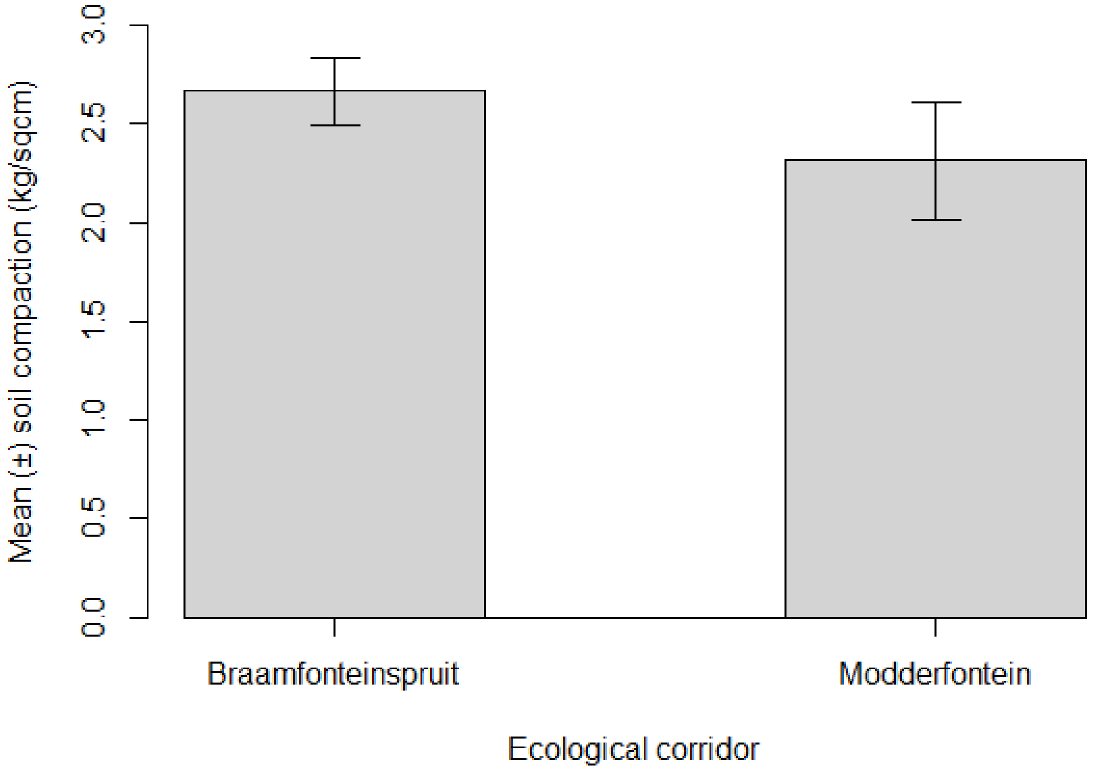

Figure 24: Mean (±SE) soil compaction (kg/cm^2) measurement within the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

The Modderfontein ecological corridor has less permeable surface areas compared to the Braamfonteinspruit corridor and the Braamfonteinspruit corridor had a much smaller area of impermeable surfaces compared to Modderfontein (Table 12).

Table 12: Percentage of floodplains and impermeable surfaces within the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

Ecological Corridor	Permeable surfaces (%)	Impermeable surfaces (%)
Braamfonteinspruit	94.8%	0.41%
Modderfontein	88.87%	11.37%

3.3.2 Temperature regulation

The mean temperature recording under trees (n = 45) within the Braamfonteinspruit corridor was 27.25 °C and the average reference point temperature in the corridor was 29.96 °C. Thus, the average cooling effect within this ecological corridor was 2.71°C. Furthermore, the average temperature under trees (n = 45) falling outside of the Braamfonteinspruit ecological corridor was 27.86 °C and the reference point had a mean temperature of 30.56 °C. Therefore, the average cooling effect outside of this corridor was 2.7 °C. Lastly, there was no significant difference (x2 = 0.017617, p = 0.01839) between the cooling effect inside and outside the Braamfonteinspruit ecological corridor (Figure 25).

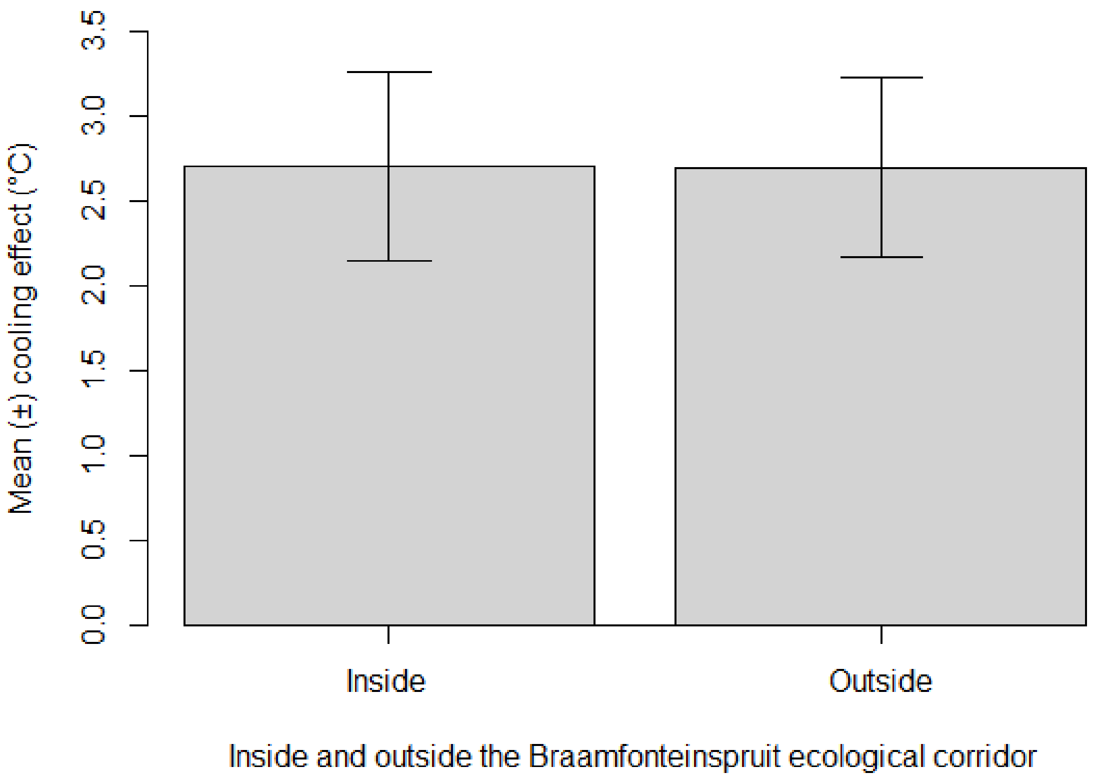

Figure 25: Mean (±SE) cooling effect (°C) outside and inside the Braamfonteinspruit ecological corridor, within Johannesburg, South Africa

The mean temperature under trees (n = 30) in the Modderfontein ecological corridor was 27.5°C and the average reference point temperature within the corridor was 30.71 °C.

Thus, the mean cooling effect within the Modderfontein corridor was 3.22 °C. Furthermore, the average temperature under trees (n = 30) outside of this corridor was 28.57 °C and the mean reference point recording outside of the corridor was 31.13 °C. Therefore, the average cooling effect outside of this corridor was 2.56 °C. Ultimately, there was no significant difference between the average cooling effect inside and outside this ecological corridor ($F_1 = 1.759$, p = 0.255) (Figure 26).

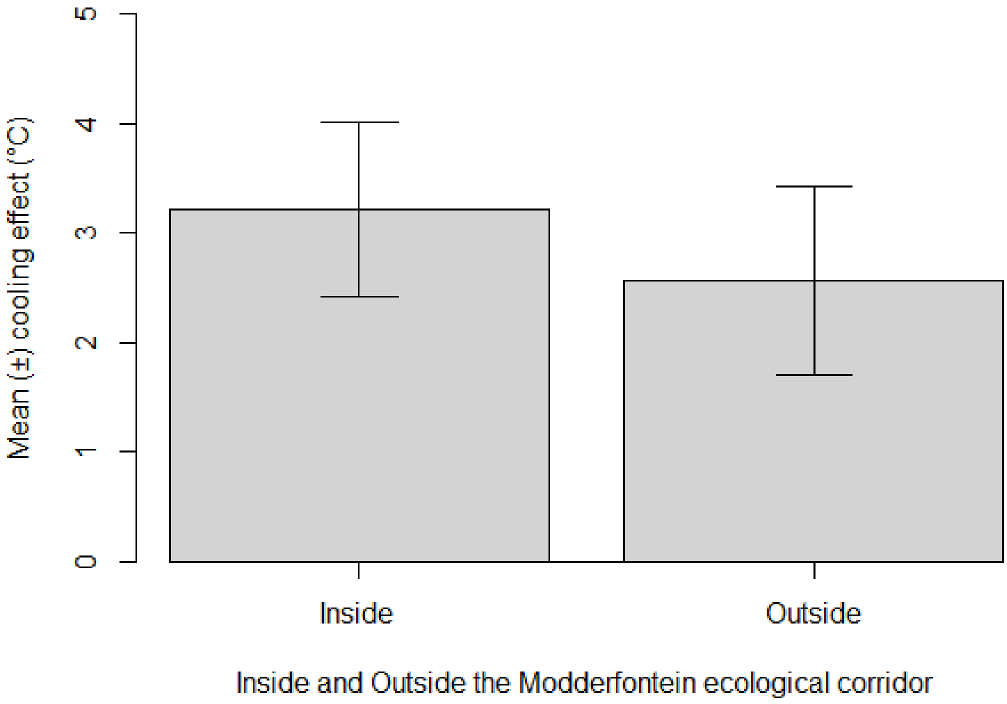

Figure 26: Mean (±SE) cooling effect (°C) outside and inside the Modderfontein ecological corridor, within Johannesburg, South Africa

The average cooling effect inside both the Braamfonteinspruit and Modderfontein ecological corridors was 2.91 °C. There was no significant difference between the cooling effect of both corridors (F = 0.291, p = 0.599) (Figure 27).

The mean cooling effect outside both the corridors was 2.64 °C. There was no significant difference between the cooling effect outside the Braamfonteinspruit and Modderfontein ecological corridors ($x^2 = 0.22222$, p = 0.6374) (Figure 27).

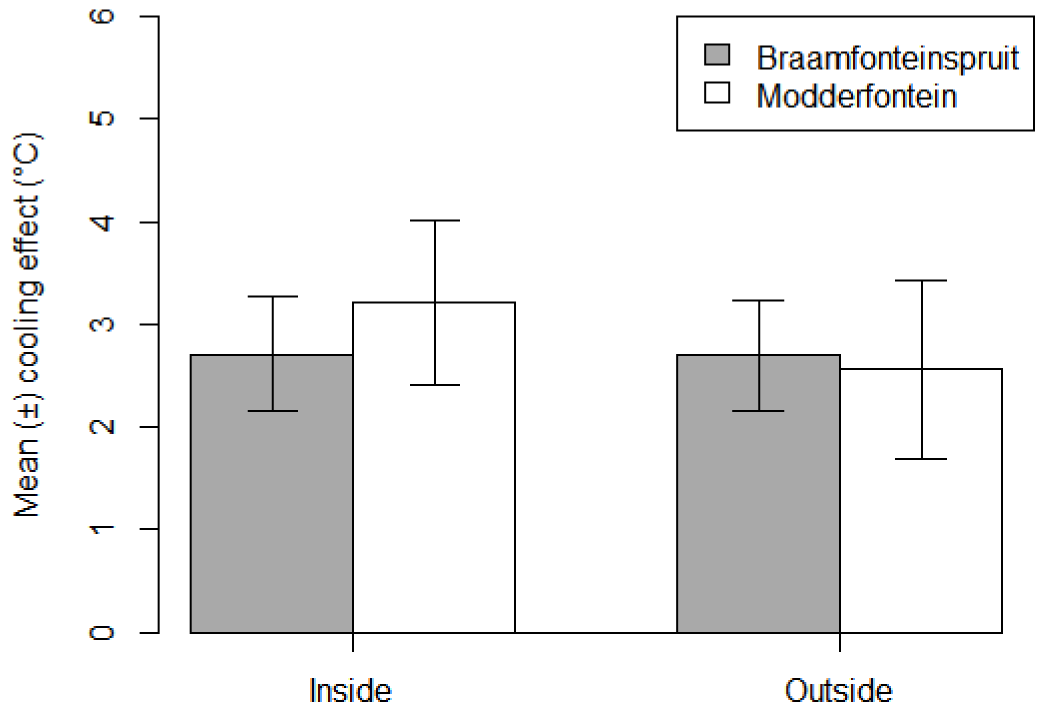

Figure 27: Mean (±SE) cooling effect °C Inside and outside the Braamfonteinspruit and Modderfontein ecological corridors, within Johannesburg, South Africa

3.3.3 Carbon sequestration

The trees (n = 30) within the Modderfontein ecological corridor have a higher average CBH (cm) and DBH (cm) value as well as a higher number of trees compared to the Braamfonteinspruit corridor (n = 45). According to both methods (Lembani, 2015, & Schäffler and Swilling, 2013) for working out total stored carbon, the Modderfontein corridor stores substantially more carbon than the Braamfonteinspruit corridor (Table 13). However, the total stored carbon values for both corridors is much lower when worked out using method 2 as compared to the substantially higher stored carbon values worked out using method 1 (Table 13).

Table 13: The total stored carbon in the Braamfonteinspruit and Modderfontein corridor , within Johannesburg, South Africa and the percentage difference between the results of Method 1 and Method 2

Ecological corridor	Total Trees	METHOD 1: Total stored carbon (tonne)	METHOD 2: Total stored carbon (tonne)	Percentage difference (%)
Braamfonteinspruit	13 535	5699.76	1182.63	131.26
Modderfontein	75 975	47324.12	13626.27	110.57

Chapter 4. DISCUSSION

South Africa faces many risks as a result of climate change, including but not limited to the Urban Heat Island, flooding and increasing CO_2 levels. A possible Ecosystem Based Adaptation strategy for South Africa and specifically the city of Johannesburg could involve the protection of ecological corridors and subsequently the ecosystem services provided by corridors. Therefore, the aim of this study was to assess the state of ecological corridors and ecosystem services in the city of Johannesburg and their potential for climate change adaptation.

4.1 Spatial analysis

Ecosystem services are influenced by various types of land use and land cover (Lehmann *et al.,* 2014). This means that any changes made to land cover and land use will directly impact surrounding ecosystems. These impacts can be negative for the environment and often lead to trade-offs between various services provided by the environment as is often the case with increasing urbanisation (Quintas-Soriano *et al.,* 2016). However, land use changes could also lead to positive impacts such as the establishment of Protected Areas which results in the enhancement of ecosystem services (Quintas-Soriano *et al.,* 2016). Land use intensity has various implications on ecosystem services and human welfare. An increase in land use intensity can lead to a decrease in regulating ecosystem services (Xu *et al.,* 2016). Therefore, the higher percentage of low intensity land use within and surrounding both the Braamfonteinspruit and Modderfontein ecological corridors suggests that the regulating ecosystem services of temperature and flood regulation as well as carbon sequestration may be minimally impacted by land use.

According to Lehmann *et al.* (2014), the more area that is covered in woodland, the better the cooling effect because it was found that vegetation consisting of many trees resulted in the greatest cooling effect. Thus, it is encouraging that the majority of land within the Braamfonteinspruit ecological corridor is covered with trees as this means that temperature regulation is supported within the corridor. Trees also take up a large percentage of land within the Modderfontein corridor, therefore it can also be concluded that this corridor has the capability of providing temperature regulation.

Kuang *et al.* (2015) conducted a study in Beijing, China that investigated the heat flux regulation of different land use types in the city. They concluded that various land use types resulted in different heat fluxes, with higher temperatures in the Central Business District of Beijing than within the parks. A study in the Guizhou Province in Southwest China concluded that land use and land cover had a direct impact on land surface temperatures (Xiao and Weng, 2007). It was found that temperatures had increased over the years as a result of the increasing built up areas including the development of residential areas, industries and shopping malls. Skyscrapers had been built with concrete and steel and factories had replaced forest and agricultural areas. A large majority of the Braamfonteinspruit and Modderfontein ecological corridors is made up of low intensity land uses such as thicket, grasses and bushland with only a very small percentage of high-intensity land uses such as roads and pavement, thus promoting cooler temperatures with both corridors

With the above studies in mind, it is promising that the majority (76.69%) of the Braamfonteinspruit corridor is covered in grassland and trees and the Modderfontein corridor is also mostly covered in grasslands and trees (69.92%). Furthermore, the perimeter of the Braamfonteinspruit corridor is mostly covered in trees (45.68%), whilst the perimeter of the Modderfontein corridor is mostly covered in open space (23.22%), grasslands (17.96%) and trees (17.88%). This suggests that areas surrounding and within both corridors are capable of regulating temperatures and can absorb heat generated from the urbanised areas within and around both the corridors. Urbanised and high intensity land use within the Braamfonteinspruit corridor such as industrial sites, residential areas, buildings, roads and smallholdings only account for 9.2% of total land use in the corridor. There is also a smaller percentage of high intensity land uses (36.09%) surrounding this corridor, meaning that there are limited urbanised structures within and around this corridor that can increase temperatures. Within the Modderfontein corridor there is high intensity and urbanised land use (9.22%) including smallholdings, residential areas, buildings, rail, industrial sites, roads as well as mines and quarries. Furthermore, there is a higher percentage of low intensity land uses (61.04%) than high intensity land uses (38.96%) surrounding this corridor, suggesting that there is limited land use within and surrounding the corridor that will increase temperatures in the Modderfontein ecological corridor.

Trees are able to sequester carbon, ultimately benefitting Earth's climate (Canadell and Raupach, 2008). Trees can help offset carbon emissions via reforestation and decreased deforestation. Through planting and rehabilitating trees in degraded areas, China was able to sequester 176.7+/-44.8 Tg C yr^{-1} of carbon from 1988 to 2001 (Wang *et al.,* 2007). However, areas covered in trees need to be managed very carefully in order to avoid disturbances such as fires which will cause the emission of significant amounts of carbon once again into the atmosphere (Canadell and Raupach, 2008). This is of particular risk in Canada where natural disturbances such as wildfires in forests can lead to the forest becoming a source of carbon instead of a carbon sink (Kurz *et al.,* 2008). Despite this, when forests are conserved and managed appropriately and sustainably, they are able to supply a magnitude of environmental services including carbon sequestration (Canadell and Raupach, 2008). Since the Braamfonteinspruit corridor is covered by 57.28 % of trees and 45.68 % of its perimeter is covered in of trees, the corridor is capable of sequestering carbon and is also benefitting from surrounding carbon sequestration. The fact that both corridors have land covered in trees is promising, however these areas should not be managed appropriately, they are at risk of becoming a carbon source. Thus, only if managed appropriately, this type of land use will help with climate change mitigation through carbon storage and sequestration (Polasky *et al.*, 2011).

A study conducted in northern Thailand found that land use changes, especially related to increasing agricultural areas, leads to soil erosion (Arunyawat and Shrestha, 2016). Arunyawat and Shrestha (2016) state that land used for agricultural purposes increases the levels of surface runoff, while land covered in forest results in decreased levels of water runoff. Since both the Braamfonteinspruit and Modderfontein ecological corridors have no agricultural land cover, this type of land use causing increased surface runoff is not a risk in these corridors. Hu *et al.* (2020) conducted a study into the effect that different types of land use, namely woodland, impervious land, water, grassland and farmland had on the surface runoff in Beijing. A negative correlation was found between surface run-off and water, woodland, farmland and grasslands, whereas there was a strong positive correlation between impervious land cover and runoff. Impervious land cover makes up around 1.88 % and 6.4 % of land within the Braamfonteinspruit and Modderfontein ecological corridors respectively, as well as 35.67 % of land surrounding the Braamfonteinspruit corridor and 30.99 % of land surrounding the Modderfontein ecological corridor. These areas may therefore contribute to an increase in surface runoff and potential flooding. However, this percentage of land cover is minimal. Grasslands make up 19.41 % of groundcover in the Braamfonteinspruit corridor, which due to the negative correlation of grasslands and surface run-off (Hu *et al.*, 2020) may help the corridor avoid flooding. The Modderfontein corridor has the most land covered in grasslands (43.06 %) which could help the corridor provide the ecosystem service of flood regulation. The Braamfonteinspruit corridor has the most land covered in woodland (57.28 %) and since woodlands are negatively correlated with surface run-off (Hu *et al.,* 2020), this type of land cover may help this corridor avoid flooding. Furthermore, woodland in the Modderfontein corridor amounts to 27.08 % which can further aid in flood regulation within this corridor. Lastly, only 5.1 % of land in the Braamfonteinspruit corridor is covered in wetlands and water, while 6.06 % of the Modderfontein corridor is covered in water and wetlands, meaning that this type of land cover may have an impact on decreasing surface run-off and thus flooding in the corridors. However, this impact is likely to be limited due to the relatively smaller land cover percentages. The thirty-three single perennial rivers within and intersecting the Braamfonteinspruit will also decrease runoff and the ninety-two single perennial rivers within and intersecting the Modderfontein corridor will help mitigate flooding.

The International Union for Conservation of Nature defines Protected Areas as areas that are managed in order to conserve nature and the ecosystem services it provides (Dudley, 2008). Protected Areas not only protect ecosystem services but can help local government and creates employment opportunities. Protected Areas form part of both an ecological and social setting. Within the well-known Table Mountain National Park in Cape Town there are 22 designated Protected Areas that help conserve the biodiversity. These Protected Areas also attract tourists and help poorer communities within the Protected Areas (Trzyna, 2007). Through land use change, climate change, the increase in alien invasive species and environmental degradation, there has been a decrease in biodiversity in the world and consequently a decrease in the number and quality of vital ecosystem services (Xu *et al.*, 2017). Therefore, it is through setting up Protected Areas that these threats can be managed and ecosystems can continue functioning. Protected Areas can help with climate change mitigation and can increase the resilience of environments (Game *et al.*, 2009).

Despite the positive impacts of having Protected Areas, the Braamfonteinspruit corridor includes no Protected Areas s and the 13 sensitive sites that intersect or are found within the corridor are not protected. According to the GDARD C-plan (2013), the Modderfontein corridor also has no protected areas even though there are 31 sensitive sites. However, it should be noted that the Modderfontein Nature Reserve that is privately managed and protected falls within this corridor, additionally Delta Park and Emmarentia Dam fall with the Braamfonteinspruit corridor and are also managed privately/commercially. Having few or no Protected Areas in ecological corridors means that biodiversity along with the ecosystem services it provides such as temperature regulation, carbon sequestration and flood regulation are not being conserved. Furthermore, Johannesburg's population is increasing and the city is continually growing in order to meet the needs of the growing population (Keeley *et al.*, 2018).

Ecological corridors in South Africa need Protected Areas in order to avoid becoming built up for further urbanisation (DEA, 2016). Clearly, both these corridors and the ecosystem services provided are at risk of rapid urbanisation in Johannesburg. Moreover, degraded natural vegetation is found in both corridors but Protected Areas can be implemented, thus restoring these degraded areas and decreasing the chance of other natural areas becoming urbanised.

4.2 Vegetation analysis

Most of Gauteng falls within the grassland biome and both the Braamfonteinspruit and Modderfontein ecological corridors are found within this biome (SANBI, 2019). It was, therefore expected that these corridors would have a high percentage of grass cover. There was a significant difference between the cover of grasses and herbs as well as grasses and bare ground in both corridors. The majority of both corridors being covered by grasslands will benefit the surrounding urban areas as grasses provide vital ecosystem services such as air purification, flood regulation, cycling of nutrients and decreased risk of soil erosion (Tongqian *et al.,* 2004). Moreover, there was no significant difference between the percentage ground cover of both corridors which consisted predominantly of grass cover, followed by herbs, bare ground and trees.

The green spaces found in urban areas are commonly made up of a variety of environments and vegetation including native plant species as well as exotic and invasive species (Lepczyk *et al.,* 2017), resulting in high levels of species richness and diversity. Grobler *et al*. (2006) investigated vegetation within 132 quadrats throughout urban spaces within Gauteng and found over 100 different species of vegetation. Furthermore, Grobler *et al.* (2002) investigated species richness within urban open areas in Gauteng, including Johannesburg. They sampled 73 quadrats and also found over 100 species. Lastly, Mckendry (2019) found 123 different grass, herb and tree species within fifteen quadrats along the Rietfontein ecological corridor in Gauteng. Compared to these studies, the Braamfonteinspruit ecological corridor that had 35 different species of vegetation recorded in the nine quadrats and the Modderfontein ecological corridor, with 25 different species recorded within six quadrats displayed, relatively low species richness.

Matthies *et al.* (2017) conducted a study of urban green spaces in Germany and found that the species richness of both indigenous and exotic plants was determined by the size of patches together with habitat heterogeneity. This means that, in order to increase species richness, urban green areas should be large enough to include a range of habitats (Matthies *et al.*, 2017). However, the Modderfontein corridor which was larger and had more habitat patches than the Braamfonteinspruit corridor did not have a higher species richness. However, the species-area relationship which explains that a larger sampling area will result in higher species richness (Rogge *et al.,* 2019) can explain why the Braamfonteinspruit where nine quadrats were set up, had a higher species richness in comparison to Modderfontein where only six quadrats were sampled from despite the Braamfonteinspruit being smaller than the Modderfontein ecological corridor. Matthies *et al.* (2017) also concluded that smaller distances between patches of green areas lead to higher levels of species richness. In addition, Püttker *et al.* (2020) investigated the impact that habitat fragmentation had on animal and plant species richness. It was found that plant numbers are negatively impacted by habitat fragmentation and fragmentation is a leading cause of species extinction. Tsuzuki *et al.* (2020) concluded that species richness increases when there is habitat connectivity and suggests that areas where connectivity exists should be conserved in order to promote endangered species. With these studies in mind, it makes sense that the Braamfonteinspruit which was very well connected, had hardly any fragmentation and had very little to no distance between green areas had a higher species richness than the Modderfontein ecological corridor which was more disconnected and had larger distances between green areas.

Hui *et al*. (2017) concluded that urban areas or cities that were relatively small but have a high Gross Domestic Product have an increased level of exotic species. This was true for the Braamfonteinspruit and Modderfontein ecological corridors that had much higher percentages of exotic species compared to native species. Clearly, the high level of exotic species found within both corridors increases overall species richness. Despite a species being exotic, it can still have the ability to supply important ecosystem services within an urban environment. For example, *Acacia mearnsii* and *Eucalyptus* trees found within the corridors can still provide regulating ecosystem services such as temperature regulation (Potgieter *et al.,* 2020).

4.3 Ecosystem services

4.3.1 Flood regulation

An Ecosystem Based Approach for flood regulation is an environmentally friendly alternative to man-made systems (Stürck *et al*., 2013). The ecosystem service of flood regulation not only benefits the environment but has a positive impact on the well- being of people (Millennium Ecosystem Assessment, 2015). Land use has a large effect on an ecosystem's ability to provide flood regulation services (Stürck *et al.,* 2013). For example, there is less of a chance that soil erosion will occur on forested land as the trees collect rainwater before it reaches the ground and their roots help combine the soil (Basarić and Bezbradica, 2016). Green spaces within an urban environment have the potential to regulate storm waters and decrease the risk of flooding (Ren *et al.,* 2020).

The physical properties of soil found within these green areas affect the ecosystem's ability to regulate flooding via water infiltration (Yang and Zhang, 2011). Having soil that can absorb storm water is particularly beneficial in an urban environment where land cover is often impermeable. Furthermore, flooding is likely to occur in an urban environment where the soil is highly compacted. (Yang and Zhang, 2011). This was apparent in the Gaza strip where total infiltration of water falls by 41% for every 1% growth in urbanisation (Eshtawi *et al.,* 2016). Soil compaction within an urban environment increases impervious ground cover, resulting in floods (Gregory *et al*., 2006; Yang and Zhang, 2011). Soil compaction means that the bulk density of the soil has risen whilst soil porosity has decreased (Boone, 1988; da Silva *et al*., 1994; Alaoui *et al.,* 2018). This causes macropores in the soil to become compacted, thus decreasing water filtration and increasing surface runoff (Alaoui *et al.*, 2018).

Amacher *et al.* (2004) used a pocket penetrometer to measure soil compression in compacted soils. Their study found that compacted soils had a mean soil compression strength of 4.4 and 4.5 kg/cm^2. The Modderfontein and Braamfonteinspruit corridors had a mean soil compression strength of 2.3 kg/cm^2 and 2.7 kg/cm^2 respectively. Therefore, the soils in both corridors can be classed as uncompacted, suggesting that both corridors have the ability to regulate flooding via water infiltration in the soil. This is in agreement with studies done by Gill *et al.* (2007) as well as Haaland and Bosch (2015) who concluded that the green areas within an urban environment have the ability to store water in the soil and decrease the amount of storm water runoff, ultimately helping to regulate floods. Byrd *et al.* (2002) investigated soil erosion and water infiltration in soils in Kentucky that were not compacted and concluded that water infiltration in these types of soils is very similar to water infiltration in forested areas of Kentucky and found that soil erosion only occurred at a small rate in the uncompact soils. Additionally, Alaoui *et al.* (2018) state that the increasing floods that have been occurring in Europe are the possible result of land dilapidation that has led to an increase in compacted soils.

Over the past ten years, Johannesburg has experienced increased rain and flooding events. In 2000, flooding occurred in the city, particularly in Alexandra Township where 233 m of rain fell between the 1st and 9th of February 2020 (Mgquba and Vogel, 2004). In 2009, Johannesburg again experienced floods because of increased rainfall throughout Soweto and in 2016 rainstorms caused flash flooding within the city. Only six months after this, flooding occurred again in 2017 as well as in December 2018 (Mvulane, 2020). Ultimately, flooding in urban areas across Johannesburg is predicted to increase as extreme weather events will become more common and intense (Mvulane, 2020). Thus, the fact that both corridors are uncompact and have the ability to regulate flooding is particularly vital in the city of Johannesburg

Zhang *et al.* (2011) investigated the effectiveness of urban green spaces in reducing water runoff by measuring the amount of water stored in these green areas. It was concluded that 2494 m^3 of water was being stored in every hectare of green space within urban Beijing. Based on this, they recommend that building new drainage facilities in urbanised areas is not only expensive but will also conserve less water. They state that rather than doing this, Beijing should invest in the permeable surfaces within green spaces in order to regulate flooding (Zhang *et al.*, 2011).

The soil compression strength inside of the protected Modderfontein Nature Reserve was significantly lower than soil compression outside of this protected reserve (but still within the ecological corridor). This could be attributed to the fact that this reserve had many trees and limited amount of people walking around on the ground. When pedestrians walk on soil, it can lead to soil compaction (Yang and Zhang, 2011). Since people are limited to driving and walking on designated roads/paths in the reserve, the majority of the soil where the vegetation and trees are found is left untouched. This could explain the less compacted soil in these sites compared to outside the reserve where the ground is often walked upon by pedestrians, and maintenance workers. Additionally, the reserve is populated by thick vegetation and many trees. Since the roots of trees decrease soil compaction (Yang and Zhang, 2011), it can further explain why the compaction in the reserve with many trees was less than outside the reserve where there was a much smaller number of trees. This means that, the trees in the reserve can further decrease soil compaction which will aid in flood regulation within the Modderfontein ecological corridor (Ren *et al.,* 2020; Bernatzky 1983), highlighting the benefit of having a reserve within an ecological corridor as it can further improve the ecosystem service of flood regulation.

Yang and Zhang (2011) concluded that soil within parks were compacted due to people walking on the ground and thus the infiltration of water was lower in these areas. Similarly, the soil compaction at site 1 in the Braamfonteinspruit corridor included Emmarentia Dam, a popular park and picnic site with many walkers. This site had significantly higher soil compaction than sites 3 and 6 which were both in more isolated and untouched areas. Furthermore, site 2 which was in Delta Park had a much higher compaction than the more isolated site 6 which could also be for similar reasons. Therefore, it can be suggested that nature reserves set up a few restricted areas as this could be more beneficial for these ecological corridors in terms of providing flood regulating ecosystem services, improving water infiltration and increasing climate change resilience in Johannesburg.

4.3.2 Temperature regulation

Interestingly, this study found no significant difference between the cooling effect of the river corridor (Braamfonteinspruit) and the greenbelt corridor (Modderfontein) with the Modderfontein corridor having a slightly higher cooling effect than Braamfonteinspruit. This differs to what was found in a study by Du *et al.* (2008) who investigated the effect that the structure of a corridor had on the surrounding areas and on the Urban Heat Island. It was found that corridors with water bodies such as a river corridor had the greatest impact on cooling the surrounding urban areas. A greenbelt also has an impact on cooling the surrounding areas, although this effect was smaller than the river corridor. Despite the greenbelt having less of an impact than water corridors, Du *et al.* (2008) still stated that the greenbelt has a considerable cooling effect and low costs, making it a useful option of cooling the Urban Heat Island within an urban environment. A potential reason that the Modderfontein corridor had a higher cooling effect than the Braamfonteinspruit corridor could be due to the small sample size. Ultimately,, corridors in general can have an impact on surrounding areas up to 300 m away (Du *et al.*, 2008).

Yokohari *et al.* (2001) investigated the effect of a green area, specifically rice paddy fields, on the surrounding suburban area in Tokyo and concluded that the paddy fields generated cool air that can flow with the wind into the residential areas. It was found that the cooling effect of the green area had an impact range of 150 m within the surrounding residential region (Yokohari *et al.,* 2001). Furthermore, a study in Japan by Hamada and Ohta (2010) found that the park within the urban area of Nagoya City allowed for cooler air to flow into the residential areas set up around the park. Air would flow as far as 200-500 m into this area. Since temperature recordings outside each of the Braamfonteinspruit and Modderfontein corridors took place around 20 m to 500 m from the corridor, it can be suggested that the corridors were cooling the surrounding areas which may account for the lack of a significant difference in the cooling effect inside and outside the Braamfonteinspruit and Modderfontein ecological corridors. Hamada *et al*. (2013) concluded that parks found within an urban environment had a cooling effect on surrounding areas. However, they did discover that the arrangement of the commercial land use surrounding the park had an impact on the spread of the cooling effect. When surrounding land use was commercial, it would block the cooling effect of the park when compared to other types of urban land use that allowed for the flow of the cooling effect. Since both corridors in this study had very high percentages of low intensity land-uses and low percentages of high intensity land uses (such as commercial land) surrounding them; it can be suggested that cool air generated inside the corridors is not hindered from flowing into surrounding areas. This may explain why areas within close proximity to both corridors only had slightly higher temperatures in the sun and in the shade compared to temperatures within the corridors. Hamada *et al*. (2013) recommends that when urban planning is taking place; in order to make the most out of the cooling effect of green areas like a park, the surrounding land uses need to be chosen carefully in order to not hinder the flow of the cooling effect from the green area into the urban area.

Els (2018) found no significant difference in the cooling effect of different land cover types within Johannesburg but did note that nature reserves within the city had the highest cooling effect compared to other land cover types such as residential, township, smallholding, commercial and industrial. Els (2018) found that residential areas had the third highest cooling effect of these different land cover types. Sonne and Vieira (2000) concluded that temperatures in a residential area with lots of trees was higher than the temperature in a forested park. They also found that when comparing a residential area with lots of vegetation to another residential area with less trees, it was cooler in the vegetated residential area (Sonne and Vieira 2000). Most temperature measurements taken outside of the Braamfonteinspruit corridor occurred within residential areas surrounded by houses with large, well maintained gardens with many trees inside the properties and lining the streets. These areas are able to generate a cooling effect of their own whilst still benefitting from cooler air flowing in from the nearby ecological corridor. Moreover, Shashua-Bar and Hoffman (2000) found that streets lined with trees were capable of lowering temperatures, leading to an overall cooling effect. Recordings taken outside of the Modderfontein ecological corridor occurred in streets that were lined with trees, suggesting that these trees together with the Modderfontein ecological corridor help cool surrounding areas.

Bowler *et al*. (2010) conducted a systematic review of various studies that assessed the impact of green areas on urban environments and found that overall, studies conclude that green areas such as parks tend to be cooler than urban areas. It was concluded that on a local scale there is evidence that green areas cool surrounding environments (Bowler *et al*., 2010). Grilo *et al.* (2020) investigated the cooling effect in urban parks and found that parks made up of a small area still have the ability to cool down surrounding environments by about 1- 3 °C. They also concluded that the higher the number of trees in a park, the greater the cooling effect (Grilo *et al.,* 2020).

Despite there not being a significant difference between the cooling effect inside and outside the Braamfonteinspruit and Modderfontein ecological corridors, both corridors had a slightly higher cooling effect than the surrounding area as well as lower average temperatures under trees and lower average reference point temperatures in the sun. Furthermore, Cao *et al.,* (2010) found that larger parks have a greater impact on cooling the surrounding urban environment. The larger the park, the greater the difference in surface temperatures between the park and the surrounding urban area. The vegetation within the green areas also has an impact on the difference in surface temperatures between urban areas and green areas. When the green area has woody vegetation that is spread out, the surface temperature difference between the green area and urban area will increase (Zhou *et al.,* 2011). There was no significant difference between the cooling effect of the two corridors, however the Modderfontein corridor did have a slightly higher cooling effect than the Braamfonteinspruit corridor. This could perhaps be attributed to the fact that the corridor was larger and has more woody vegetation than the Braamfonteinspruit corridor. The lack of a significant difference between the cooling effect inside and outside both corridors can be attributed to the fact that the surrounding areas of both corridors were also covered in a large percentage of trees and low intensity land uses it. The lack of a significant difference between the cooling effect inside and outside the corridors does not prove that the corridors are incapable of regulating temperature. Both corridors can contribute to cooling in the city as the cooling effect is not limited or blocked by high intensity land uses that could hinder air flow into surrounding areas. The fact that areas surrounding the corridors were green only adds to the cooling effect of the corridors and can help regulate temperatures in the city.

4.3.2 Carbon Sequestration

There are various factors that can affect the level of success that urban green areas have in sequestering carbon such as the age and species of trees within the forest (Zhao *et al.,* 2010) as well as how people manage these areas (Nowak *et al*., 2013). It should be noted that when trees die, the carbon stored is released into the surrounding environment (Nowak *et al.*, 2013). Various studies have concluded that green spaces within an urban environment, whether it be parks, green roofs, forest or corridors, are a beneficial climate change adaptation strategy owing to the fact that vegetation within these areas can sequester carbon in the urban environment and store it as biomass (Nowak and Crane, 2002; Pataki *et al*., 2006; Vidrih and Medved, 2013).

Two different methods involving allometric equations were used in this study to quantify total stored carbon. It was found via both methods that the Modderfontein corridor which has more trees as well as trees with a larger average Circumference at Breast Height, is likely to store more carbon than trees in the Braamfonteinspruit corridor. There was a difference in the carbon storage results based on method 1 and method 2; with method 1 leading to lower values and method 2 resulting in overall higher values. Els (2018) also found that stored carbon values at the majority of their sites were higher using method 1 compared to method 2. Despite the different values yielded by both methods, it can be concluded that the Modderfontein ecological corridor stores more carbon than the Braamfonteinspruit ecological corridor.

A study by Velasco *et al*. (2016) concluded that in Mexico City, larger trees were most common and these large trees had a positive impact on carbon sequestration. Furthermore, it was found that in Singapore, despite having fewer large trees, it was these larger trees that contained the highest amount of tree biomass (95.3%) and thus it was the larger trees that stored the most carbon (Velasco *et al*., 2016). Since the trees in the Modderfontein ecological corridor were on average larger than trees in the Braamfonteinspruit corridor, it can explain why more carbon may be stored in this corridor. According to Nowak and Crane (2002), a tree found in an urban area holds more than 4 times as much carbon than a tree found within a forest and they explain that this is again due to the differences in tree size. A larger tree has a greater diameter which ultimately means the tree has more biomass available to store larger levels of carbon. According to Mildrexler *et al.* (2020), areas where larger trees are found need to be protected for carbon sequestration purposes as well as to prevent carbon from being released into the atmosphere when trees are cut down.

Given the urgency of keeping additional carbon out of the atmosphere and continuing carbon accumulation from the atmosphere to protect the climate system, it would be prudent to continue protecting ecosystems with large trees for their carbon stores, and also for their co-benefits of habitat for biodiversity, resilience to drought and fire, and microclimate buffering under future climate extremes.

Gratani *et al*. (2016) conducted a study of four parks within Rome and calculated carbon sequestration; it was concluded that the larger the area of vegetated surfaces, the larger the carbon sequestration. The same can be applied to this study where the Modderfontein corridor stored more carbon than the Braamfonteinspruit owing to the fact that Modderfontein had a much higher total area as well as a higher number of vegetated surfaces and trees, meaning that it is capable of sequestering more carbon than the Braamfonteinspruit corridor.

Els (2018) found that in Johannesburg, poorer areas with fewer trees likely store much less carbon compared to residential areas with larger number of trees. Moreover,, according to Schäffler and Swilling (2013), the northern and more affluent areas of Johannesburg have higher tree cover compared to poorer areas in the southern parts of Johannesburg. Since both corridors run through affluent areas in the north of Johannesburg, it may account for the high percentage land cover of trees, grasses and vegetated areas in the corridors. This increases the capability of both corridors to sequester carbon and provide other ecosystem services. Clearly, there is a need for the City of Johannesburg to increase green cover in poorer areas of Johannesburg in order for distribute the access to ecosystem services and climate change resilience more equally. Els (2018) also found that nature reserves in Johannesburg store low amounts of carbon. This was not concluded in this study where the Modderfontein ecological corridor which has a large nature reserve within it, stored higher amounts of carbon. Els (2018) attributed the small levels of carbon storage in the reserve to smaller trees, however this was not the case in the Modderfontein ecological corridor.

In order for the whole of Johannesburg to benefit from carbon sequestration, greener areas need to be set up across the city. Furthermore, in order to maximise carbon sequestration provided by an ecological corridor, the corridor should cover a large amount of space and larger trees should be spread throughout the corridor.

4.4 Conclusion

This study found that both the Braamfonteinspruit and Modderfontein ecological corridors in Johannesburg are covered in grasslands, have a high herbaceous species richness and a large number of trees despite the surrounding urbanisation. This level of biodiversity in the midst of urbanised Johannesburg can help the city and its residents adapt to climate change.

The fact that both corridors had low soil compaction means that these green areas can help regulate floods resulting from climate change via water infiltration. Due to impervious surfaces in urbanised Johannesburg, the risk of storm water runoff is increased. However, green spaces in the city can absorb excess water and the Braamfonteinspruit and Modderfontein ecological corridors can help avoid flooding, increasing climate change adaptation in the city.

Since there was no significant difference in the cooling effect outside and within both corridors, it seems to suggest that both corridors do not produce a cooling effect. However, it must be noted that the cooling effect of these corridors was only measured in areas very near to the corridor and were also taken within areas surrounded by gardens and trees. Therefore, it cannot be said with certainty that the corridors do not produce a cooling effect. Lastly, trees in both the Braamfonteinspruit and Modderfontein ecological corridors can store carbon as biomass and provide the ecosystem service of carbon sequestration, However, the effectiveness of providing this service is improved when the number and size of trees is increased which is why the Modderfontein corridor stores more carbon than the Braamfonteinspruit corridor.

Ultimately, this study found that both the Braamfonteinspruit and Modderfontein ecological corridors provide vital ecosystem services of flood regulation and carbon sequestration. Despite the fact that further investigation would be needed to state that both corridors provide the service of temperature regulation; the large percentage of trees found within both corridors does suggest that some level of temperature regulation is taking place. These corridors need to be protected in order to increase the quality of the ecosystem services they provide as well as ensure that these services continuously be provided as the impacts of climate change worsen. It is recommended that these corridors as well as others spread across Johannesburg be used as a strategy to help the city and its residents adapt to the great risk that is climate change.

4.5 Limitations

This study provides a vegetation analysis of the Braamfonteinspruit and Modderfontein ecological corridors in order to investigate the functionality of the corridors and its ability to provide ecosystem services. However, only a small number of quadrats within both corridors were investigated. In order for results to be more reliable, three quadrats within each study site along both corridors should be sampled. Furthermore, soil compaction measurements that informed flood regulation capabilities of the corridors was measured using a pocket penetrometer. In order to receive more reliable results, a cone penetrometer could be used. The large percentage difference between the two methods used to quantify carbon storage makes the results less reliable, an alternative carbon storage calculation with higher accuracy should be used. In order to estimate the impact of the corridors' cooling effect, temperature measurements should be taken within the city centre instead of taken right outside each corridor as was done in this study. In order to increase the reliability of results, an increased number of temperature, soil compaction and tree measurements should take place. However, due to time constraints this was not possible for this study. Despite the limitations of this study, the results do give an idea of the effectiveness of ecosystem services and the functionality of ecological corridors within Johannesburg.

References

Aboelata, A., Sodoudi, S., 2020. Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. Building and Environment 168, 106-490.

Akubia, J.E.K., Ahmed, A., Bruns, A., 2020. Assessing How Land-Cover Change Associated with Urbanisation Affects Ecological Sustainability in the Greater Accra Metropolitan Area, Ghana. Land 9, 182.

Alaoui, A., Rogger, M., Peth, S., Blöschl, G., 2018. Does soil compaction increase floods? A Review. Journal of Hydrology 557,631-642.

Aquilué, N., Messier, C., Martins, K.T., Dumais-Lalonde, V., Mina, M., 2021. A simple-to-use management approach to boost adaptive capacity of forests to global uncertainty. Forest Ecology and Management 481, 118692.

Atif, S.B., 2018. Identification of Key-Trends and Evaluation of Contemporary Research Regarding Urban Ecosystem Services: A Path towards Socio-Ecological Sustainability of Urban Areas. Applied Ecology and Environmental Research 16, 3545–3581.

Austin, G.D., 2012. Multi-Functional Ecological Corridors in Urban Development. Spaces and Flows: An International Journal of Urban and ExtraUrban Studies 2, 211–228.

Basarić, J., Bezbradica, L., 2016. Analysis of the Kolubara Drainage Basin and Impacts of The River on the Town of Valjevo and its Surroundings. Presented at the 3rd International Conference "Water resources and wetlands, Romanian Limnogeographical Association, Romania, 146–152.

Bernatzky, A., 1983. The effects of trees on the urban climate. In: Trees in the 21st Century. Academic Publishers, Berkhamster, 59-67.

Bolund, P., Hunhammar, S., 1999. Ecosystem services in urban areas. Ecological Economics 29, 293–301.

Boone, F.R., 1988. Weather and other environmental factors influencing crop responses to tillage and traffic. Soil and Tillage Research (Netherlands) 11, 283-324.

Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and Urban Planning 97, 147–155.

Braun-Blanquet, J., 1932. Plant sociology. (transl. G.D.Fuller and H.S.Conard). McGraw Hill, New York.

Bryant, M.M., 2006. Urban landscape conservation and the role of ecological greenways at local and metropolitan scales. Landscape and Urban Planning 76, 23–44.

Burkhard, B., Maes, J. (Eds.), 2017. Mapping Ecosystem Services. Pensoft Publishers, Bulgaria.

Byrd, E.J., Kolka, R.K., Warner, R.C., Ringe, J.M., 2002. Soil Water Percolation and Erosion on Uncompacted Surface Mine Soil in Eastern Kentucky. JASMR 2002, 1049–1059.

Cahill, A.E., Aiello-Lammens, M.E., Fisher-Reid, M.C., Hua, X., Karanewsky, C.J., Yeong Ryu, H., Sbeglia, G.C., Spagnolo, F., Waldron, J.B., Warsi, O., Wiens, J.J., 2013. How does climate change cause extinction? Proceedings of the Royal Society B: Biological Sciences 280, 20121890.

Cao, X., Onishi, A., Chen, J., Imura, H., 2010. Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. Landscape and Urban Planning 96, 224–231.

Chang, S.C., Tu, C.J., Chen, H.Y., 2010. Ecological Corridor in the Urban Area: Case Study in Kaohsiung City, Taiwan. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management 14, 76–88.

Chen, W.Y., 2015. The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: A nationwide estimate. Cities 44, 112–120.

Cilliers, S., Cilliers, J., Lubbe, R., Siebert, S., 2013. Ecosystem services of urban green spaces in African countries—perspectives and challenges. Urban Ecosystems 16, 681–702.

Cilliers, S., du Toit, M., Cilliers, J., Drewes, E., Retief, F., 2014. Sustainable urban landscapes: South African perspectives on transdisciplinary possibilities. Landscape and Urban Planning 125, 260–270.

City of Johannesburg., 2018. About the City [WWW Document]. City of Johannesburg. URL https://www.joburg.org.za/ (accessed 3.2.19).

City of Johannesburg., 2018. Climate [WWW Document]. City of Johannesburg. URL https://www.joburg.org.za/media_/Newsroom/Pages/2012%20Articles/Climate-change-affects-health-.aspx#:~:text=Models%20suggest%20that%20temperatures%20for,2100)%2C%E2%80%9D%20Kgope%20explained (accessed 25.2.21).

Gil-Agudelo, D.L., Cintra-Buenrostro, C.E., Brenner, J., González-Díaz, P., Kiene, W., Lustic, C., Pérez-España, H., 2020. Coral Reefs in the Gulf of Mexico Large Marine Ecosystem: Conservation Status, Challenges, and Opportunities. Frontiers in Marine Science 6, 807.

Closset-Kopp, D., Wasof, S., Decocq, G., 2016. Using process-based indicator species to evaluate ecological corridors in fragmented landscapes. Biological Conservation 201, 152–159.

Cook, E.A., 2002. Landscape structure indices for assessing urban ecological networks. Landscape and urban planning 58, 269–280.

Curcic, N., Djurdjic,S., 2013. The actual relevance of ecological corridors in nature conservation. Journal of the Geographical Institute Jovan Cvijic 63, 21-34.

Da Silva, A.P., Kay, B.D., Perfect, E., 1994. Characterization of the least limiting water range of soils. Soil Science Society of America (USA) 58, 1775-1781.

Dang, T.N., Van, D.Q., Kusaka, H., Seposo, X.T., Honda, Y., 2018. Green Space and Deaths Attributable to the Urban Heat Island Effect in Ho Chi Minh City. American Journal of Public Health 108, S137–S143.

Department of Environmental Affairs (DEA) (2016) National Protected Areas Expansion Strategy for South Africa 2016. Department of Environmental Affairs, Pretoria, South Africa.

Department of Environmental Affairs (DEA)., South African National Biodiversity Institute (SANBI)., 2017. Ecosystem Based Adaptation (EbA): Guidelines in South Africa. Department of Environmental Affairs, Pretoria, South Africa.

Dingaan, M.N.V., Preez, P.J. du., 2017. Floristic composition and species diversity of urban vegetation in Bloemfontein, Free State, South Africa. Bothalia 47, 15.

Du, M., Sun, W., Chen, Y., 2008. Impact of Corridor Structure on Urban Heat Island in Beijing, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 37, 1-4.

Els, V., 2018. Urban Ecosystem Services in Johannesburg, South Africa. Msc thesis. University of the Witwatersrand, Johannesburg, South Africa

ESRI. 2017. ArcGIS Desktop 10.5.1 Environmental Systems Research Institute, Redlands.

Eshtawi, T., Evers, M., Tischbein, B., 2016. Quantifying the impact of urban area expansion on groundwater recharge and surface runoff. Hydrological Sciences Journal 61, 826–843.

Forman, R.T.T., 1995. Land Mosaics: The Ecology of Landscape and Regions. Cambridge University Press, Cambridge, UK.

Gauteng Department of Agriculture and Rural Development (GDARD), 2013. Conservation Plan 2 for South Africa. Gauteng Department of Agriculture and Rural Development, Gauteng, South Africa.GEOTERRAIMAGE, 2014. Gauteng land cover/use 2.5m.(v3).

GEOTERRAIMAGE, 2014. General notes and naming conventions as used in the National

Land-Use © Change data product as prepared for GCRO and the wider GCR area.

Gill, S., Handley, J.F., Ennos, R., Pauleit, S., 2007. Adapting Cities for Climate Change: The Role of the Green Infrastructure. Built Environment 33, 115–133.

Gómez-Baggethun, E., Barton, D.N., 2013. Classifying and valuing ecosystem services for urban planning. Ecological Economics 86, 235–245.Gratani, L., Varone, L., Bonito, A., 2016. Carbon sequestration of four urban parks in Rome.

Urban Forestry & Urban Greening, Special Section: Power in urban social-ecological systems: Processes and practices of governance and marginalization 19, 184–193.

Gregory, J.H., Dukes, M.D., Jones, P.H., Miller, G.L., 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61, 117–124.

Grilo, F., Pinho, P., Aleixo, C., Catita, C., Silva, P., Lopes, N., Freitas, C., Santos-Reis, M., McPhearson, T., Branquinho, C., 2020. Using green to cool the grey: Modelling the cooling effect of green spaces with a high spatial resolution. Science of The Total Environment 724, 138-182.

Grobler, C.H., Bredenkamp, G.J., Brown, L.R., 2002. Natural woodland vegetation and plant species richness of the urban open spaces in Gauteng, South Africa. Koedoe 45, 19–34.

Grobler, C.H., Bredenkamp, G.J., Brown, L.R., 2006. Primary grassland communities of urban open spaces in Gauteng, South Africa. South African Journal of Botany 72, 367–377.

Haaland, C., van den Bosch, C.K., 2015. Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban forestry &urban greening 14, 760-771.

Hamada, S., Ohta, T., 2010. Seasonal variations in the cooling effect of urban green areas on surrounding urban areas. Urban Forestry & Urban Greening 9,15–24.

Hamada, S., Tanaka, T., Ohta, T., 2013. Impacts of land use and topography on the cooling effect of green areas on surrounding urban areas. Urban Forestry & Urban Greening 12, 426–434.

Heller, N.E., Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation 142, 14–32.

Hui, C., Richardson, D.M., Visser, V., 2017. Ranking of invasive spread through urban green areas in the world's 100 most populous cities. Biol Invasions 19, 3527–3539

Hulme, P.E., 2005. Adapting to climate change: is there scope for ecological management in the face of a global threat?: Adaptive management in the face of climate change. Journal of Applied Ecology 42, 784–794.

Keeley, A.T.H., Ackerly, D.D., Basson, G., Cameron, D.R., Hannah, L., Heller, N.E., Huber, R., Roehrdanz, P.R., Schloss, C.A., Thorne, H., Veloz, S., Merenlender, A.M., 2018. Climate-wise Landscape Connectivity: Why, How, and What Next. California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CNRA-CCC4A-2018-XXX.

Kubei, J., 1996. Biocentres and Corridors in a Cultural Landscape. A Critical Assessment of the Territorial System of Ecological Stability. Landscape and Urban Planning 35, 23l–240.

Laros, C.M., Birch, S., Clover, J., 2013. Ecosystem-based approaches to building resilience in urban areas: towards a framework for decision-making criteria. Background Paper. ICLEI-Africa.Lembani, R. L., 2015. Greening Soweto: calculating above-ground tree biomass, stored carbon and net economic value. MSc thesis, University of the Witwatersrand, Johannesburg, South Africa.

Lepczyk, C.A., Aronson, M.F.J., Evans, K.L., Goddard, M.A., Lerman, S.B., MacIvor, J.S., 2017. Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. BioScience 67, 799–807.

Li, W.F., Wang, Y.L., Jiang, Y.Y., Li, G.C., 2003. Spatial approaches to ecological regulation in urban areas: a case in Shenzhen. Acta Ecologica Sinica 23(9), 1823–1831.

Martin AR, Thomas SC. 2011. A Reassessment of Carbon Content in Tropical Trees. PLoS ONE 6(8): e23533. doi:10.1371/journal.pone.0023533.

Martínez-Harms, M.J., Balvanera, P., 2012. Methods for mapping ecosystem service supply: a review. International Journal of Biodiversity Science, Ecosystem Services & Management 8, 17–25.

Matthies, S.A., Rüter, S., Schaarschmidt, F., Prasse, R., 2017. Determinants of species richness within and across taxonomic groups in urban green spaces. Urban Ecosyst 20, 897–909.

Mckendry, T., 2019. Ecological corridors in urban landscapes: identifying and assessing an ecological corridor in Johannesburg. Msc thesis. University of the Witwatersrand, Johannesburg, South Africa.

McPhearson, T., Hamstead, Z.A., Kremer, P., 2014. Urban Ecosystem Services for Resilience Planning and Management in New York City. AMBIO 43, 502–515.

Mgquba, S.K., Vogel, C., 2004. Living with environmental risks and change in Alexandra Township. South African Geographical Journal 86:1, 30-380.

Mildrexler, D.J., Berner, L.T., Law, B.E., Birdsey, R.A., Moomaw, W.R., 2020. Large Trees

Dominate Carbon Storage in Forests East of the Cascade Crest in the United States Pacific Northwest. Frontiers in Forests and Global Change 3, 127.

Millennium Ecosystem Assessment, 2015. Millennium Ecosystem Assessment Synthesis Report. Washington.

Moser, S.C., Ekstrom, J.A., 2010. A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences 107, 22026–22031.

Mueller-Dombois, D., Ellenberg, H., 1974. Aims and Methods of Vegetation Ecology. John Wiley & Sons, United States of America.

Munroe, R., Jenner, N., 2019. Ecosystem-based approaches for adaptation and impacts of adaptation activities on biodiversity [WWW Document]. Bird Life International. URL https://www.birdlife.org/projects/9-ecosystem-based-approaches-adaptation-and-impacts-adaptation-activities-biodiversity (accessed 3.12.19).

Mvulane, P., 2020. Settling on water pathways: A case study of Setswetla vulnerability to flash floods. Msc thesis. University of the Witwatersrand, Johannesburg, South Africa

Nor, A.N.M., Corstanje, R., Harris, J.A., Grafius, D.R., Siriwardena, G.M., 2017. Ecological connectivity networks in rapidly expanding cities. Heliyon 3, e00325.

Nowak, D.J., Crane, D.E., 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution 116, 381–389.

Nowak, D.J., Greenfield, E.J., Hoehn, R.E., Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. Environmental Pollution 178, 229–236.

Pataki, D.E., Alig, R.J., Fung, A.S., Golubiewski, N.E., Kennedy, C.A., Mcpherson, E.G., Nowak, D.J., Pouyat, R.V., Lankao, P.R., 2006. Urban ecosystems and the North American carbon cycle. Global Change Biology 12, 2092–2102.

Peng, J., Zhao, H., Liu, Y., 2017. Urban ecological corridors construction: A review. Acta Ecologica Sinica 37, 23–30.

Pfab, M.F., Compaan, P.C., Whittington-Jones, C.A., Engelbrecht, I., Dumalisile, L., Mills, L., West, S.D., Muller, P., Masterson, G.P.R., Nevhutalu, L.S., Holness, S.D., Hoare, D.B., 2017. The Gauteng Conservation Plan: Planning for biodiversity in a rapidly urbanising province. Bothalia 47.

Püttker, T., Crouzeilles, R., Almeida-Gomes, M., Schmoeller, M., Maurenza, D., Alves-Pinto, H., Pardini, R., Vieira, M.V., Banks-Leite, C., Fonseca, C.R., Metzger, J.P., Accacio, G.M., Alexandrino, E.R., Barros, C.S., Bogoni, J.A., Boscolo, D., Brancalion, P.H.S., Bueno, A.A., Cambui, E.C.B., Canale, G.R., Cerqueira, R., Cesar, R.G., Colletta, G.D., Delciellos, A.C., Dixo, M., Estavillo, C., Esteves, C.F., Falcão, F., Farah, F.T., Faria, D., Ferraz, K.M.P.M.B., Ferraz, S.F.B., Ferreira, P.A., Graipel, M.E., Grelle, C.E.V., Hernández, M.I.M., Ivanauskas, N., Laps, R.R., Leal, I.R., Lima, M.M., Lion, M.B., Magioli, M., Magnago, L.F.S., Mangueira, J.R.A.S., Marciano-Jr, E., Mariano-Neto, E., Marques, M.C.M., Martins, S.V., Matos, M.A., Matos, F.A.R., Miachir, J.I., Morante-Filho, J.M., Olifiers, N., Oliveira-Santos, L.G.R., Paciencia, M.L.B., Paglia, A.P., Passamani, M., Peres, C.A., Pinto Leite, C.M., Porto, T.J., Querido, L.C.A., Reis, L.C., Rezende, A.A., Rigueira, D.M.G., Rocha, P.L.B., Rocha-Santos, L., Rodrigues, R.R., Santos, R.A.S., Santos, J.S., Silveira, M.S., Simonelli, M., Tabarelli, M., Vasconcelos, R.N., Viana, B.F., Vieira, E.M., Prevedello, J.A., 2020. Indirect effects of habitat loss via habitat fragmentation: A cross-taxa analysis of forest-dependent species. Biological Conservation 241, 108368.

Potgieter, L.J., Douwes, E., Gaertner, M., Measey, J., Paap, T., Richardson, D.M., 2020. Biological Invasions in South Africa’s Urban Ecosystems: Patterns, Processes, Impacts, and Management, in: van Wilgen, B.W., Measey, J., Richardson, D.M., Wilson, J.R., Zengeya, T.A. (Eds.), Biological Invasions in South Africa. Springer International Publishing, Cham, pp. 275–309.

Ren, X., Hong, N., Li, L., Kang, J., Li, J., 2020. Effect of infiltration rate changes in urban soils on stormwater runoff process. Geoderma 363.

Rocha, M.E.R.R., Ramos, R.A.R., 2012. Network of urban parks and green corridors in the city of Braga, Portugal. Presented at the EED ’12 - The 10th WSEAS International Conference on Environment, Ecosystems and Development, World Scientific and Engineering Academy and Society (WSEAS), 205–210.

Rogge, T., Jones, D., Drossel, B., Allhoff, K.T., 2019. Interplay of spatial dynamics and local adaptation shapes species lifetime distributions and species-area relationships. THEORETICAL ECOLOGY 12, 437–451.

RStudio Team, 2019. RStudio: Integrated Development Environment for R, Boston, MA. Available at: http://www.rstudio.com/.

Schäffler, A., Swilling, M., 2013. Valuing green infrastructure in an urban environment under pressure-the Johannesburg case. Ecological Economics, 86, 246-257.

Schmidt, C., Domaratzki, M., Kinnunen, R.P., Bowman, J., Garroway, C.J., 2020. Continent-wide effects of urbanization on bird and mammal genetic diversity. Proceedings of the Royal Society B: Biological Sciences 287, 2019-2497.

Scott, D., Lemieux, C., 2005. Climate change and protected area policy and planning in Canada. The Forestry Chronicle 81, 696–703.

Shashua-Bar, L., Hoffman, M.E., 2000. Vegetation as a climatic component in the design of an urban street An empirical model for predicting the cooling effect of urban green areas with trees 15.

Sigwela, A., Elbakidze, M., Powell, M., Angelstam, P., 2017. Defining core areas of ecological infrastructure to secure rural livelihoods in South Africa. Ecosystem Services, Investing in ecological infrastructure in South Africa 27, 272–280.

Sonne, J., Vieira, R., 2000. Cool Neighborhoods: The Measurement of Small Scale Heat Islands, in: Proceedings ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy-Efficient Economy, Washington.

South African National Biodiversity Institute (SANBI)., 2019. National biodiversity assessment 2018: the status of South Africa’s ecosystems and biodiversity: synthesis report. South African National Biodiversity Institute, Pretoria.

South African Weather Service (SAWS)., 2016. Johannesburg temperature records [WWW Document]. South African Weather Service. URL http://www.weathersa.co.za/climate/historical-rain-maps (accessed 15.3.16).

Stürck, J., Poortinga, A., Verburg, P.H., 2013. Mapping ecosystem services: The supply and demand of flood regulation services in Europe. Ecological Indicators 38, 198–211.

Tanner, T., Mitchell, T., Polack, E., Guenther, B., 2009. Urban Governance for Adaptation: Assessing Climate Change Resilience in Ten Asian Cities. IDS Working Papers 2009, 01–47.

Thomas, S.C., Malczewski, G., 2007. Wood carbon content of tree species in eastern China: Interspecific variability and the importance of the volatile fraction. Journal of Environmental Management, 85, 659-662.

Tietema, T., 1993. Biomass determination of fuelwood trees and bushes of Botswana, Southern Africa. Forest Ecology and Management, 60, 257-269.

Tongqian, Z., Zhiyun, O., Liangqing, J., Hua, Z., 2004. Ecosystem services and their valuation of China grassland. Acta Ecologica Sinica 24, 1101–1110.

Townsend, P.A., Masters, K.L., 2015. Lattice-work corridors for climate change: a conceptual framework for biodiversity conservation and social-ecological resilience in a tropical elevational gradient. Ecology and Society 20.

Tsuzuki, Y., Koyanagi, T.F., Miyashita, T., 2020. Plant community assembly in suburban vacant lots depends on earthmoving legacy, habitat connectivity, and current mowing frequency. Ecol Evol 10, 1311–1323.

van de Sand, I., Mwangi, J.K., Namirembe, S., 2014. Can Payments for Ecosystem Services Contribute to Adaptation to Climate Change? Insights from a Watershed in Kenya. Ecology and Society 19.

Velasco, E., Roth, M., Norford, L., Molina, L.T., 2016. Does urban vegetation enhance carbon sequestration? Landscape and Urban Planning 148, 99–107.

Vidrih, B., Medved, S., 2013. Multiparametric model of urban park cooling island. Urban Forestry & Urban Greening 12, 220–229.

Warhurst, J.R., Parks, K.E., McCulloch, L., Hudson, M.D., 2014. Front gardens to car parks: changes in garden permeability and effects on flood regulation. Science of Total Environment 485–486, 329–339.

Waugh, D., 2000. Geography: An Integrated Approach. Nelson Thornes.

Yang, J.L., Zhang, G.L., 2011. Water infiltration in urban soils and its effects on the quantity and quality of runoff. Journal of Soils and Sediments 11, 751–761.

Yokohari, M., Brown, R.D., Kato, Y., Yamamoto, S., 2001. The cooling effect of paddy fields on summertime air temperature in residential Tokyo, Japan. Landscape and Urban Planning 53, 17–27.

Zhang, B., Xie, G., Xue, K., Wang, J., Xiao, Y., Zhang, C., 2011. Evaluation of rainwater runoff storage by urban green spaces in Beijing. Shengtai Xuebao/ Acta Ecologica Sinica 31, 3839–3845.

Zhao, M., Kong, Z., Escobedo, F.J., Gao, J., 2010. Impacts of urban forests on offsetting carbon emissions from industrial energy use in Hangzhou, China. Journal of Environmental Management 91, 807–813.

Zhou, W., Huang, G., Cadenasso, M.L., 2011. Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. Landscape and Urban Planning 102, 54–63.

Zhu, Q., Yu, K., Li, D.H., 2005. The width of ecological corridor in landscape planning. Acta Ecoliga Sinica 25, 92406–2412.

Schüler, G., 2006. Identification of flood-generating forest areas and forestry measures for water retention. For. Snow Landsc. Res. 16.

Gillings, S., Balmer, D.E., Fuller, R.J., 2015. Directionality of recent bird distribution shifts and climate change in Great Britain. Glob Chang Biol 21, 2155–2168.

Arunyawat, S., Shrestha, R.P., 2016. Assessing Land Use Change and Its Impact on

Ecosystem Services in Northern Thailand. Sustainability 8, 768.

Canadell, J.G., Raupach, M.R., 2008. Managing Forests for Climate Change Mitigation. Science 320, 1456–1457.

Dudley, N., 2008. Guidelines for Applying Protected Area Management Categories. IUCN, Gland, Switzerland.

Game, E.T., Bode, M., McDonald-Madden, E., Grantham, H.S., Possingham, H.P., 2009. Dynamic marine protected areas can improve the resilience of coral reef systems. Ecol. Lett. 12, 1336–1346.

Hu, Fan, Zhang., 2020. Assessing the Effect of Land Use Change on Surface Runoff in a Rapidly Urbanized City: A Case Study of the Central Area of Beijing. Land 9, 17.

Kuang, W., Dou, Y., Zhang, C., Chi, W., Liu, A., Liu, Y., Zhang, R., Liu, J., 2015. Quantifying the heat flux regulation of metropolitan land use/land cover components by coupling remote sensing modeling with in situ measurement. Journal of Geophysical Research: Atmospheres 120, 113–130.

Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C., Neilson, E.T., 2008. Risk of natural disturbances makes future contribution of Canada’s forests to the global carbon cycle highly uncertain. Proc. Natl. Acad. Sci. U.S.A. 105, 1551–1555.

Lehmann, I., Bräuer, A., Mathey, J., Rößler,, S., Goldberg, V., 2014. Urban vegetation structure types as a methodological approach for identifying ecosystem services-Application to the analysis of micro-climatic effects. Ecological indicators.

Polasky, S., Nelson, E., Pennington, D., Johnson, K.A., 2011. The Impact of Land-Use Change on Ecosystem Services, Biodiversity and Returns to Landowners: A Case Study in the State of Minnesota. Environ Resource Econ 48, 219–242.

Quintas-Soriano, C., Castro, A.J., Castro, H., García-Llorente, M., 2016. Impacts of land use change on ecosystem services and implications for human well-being in Spanish drylands. Land Use Policy 54, 534–548.

Trzyna, T.C., 2007. Global urbanization and protected areas: challenges and opportunities posed by a major factor of global change -- and creative ways of responding, CIPA publication. InterEnvironment/California Institute of Public Affairs, Sacramento, CA.

Wang, S., Chen, J.M., Ju, W.M., Feng, X., Chen, M., Chen, P., Yu, G., 2007. Carbon sinks and sources in China’s forests during 1901–2001. Journal of Environmental Management, Carbon Sequestration In China’s Forest Ecosystems 85, 524–537.

Xiao, H., Weng, Q., 2007. The impact of land use and land cover changes on land surface temperature in a karst area of China. Journal of Environmental Management 85, 245–257.

Xu, W., Xiao, Yi, Zhang, J., Yang, W., Zhang, lu, Hull, V., Wang, Z., Zheng, H., Liu, J., Polasky, S., Jiang, L., Xiao, Yang, Shi, X., Rao, E., Lu, F., Wang, X., Daily, G., Ouyang, Z., 2017. Strengthening protected areas for biodiversity and ecosystem services in China. Proceedings of the National Academy of Sciences 114, 201620503.

Xu, Y., Tang, H., Wang, B., Chen, J., 2016. Effects of land-use intensity on ecosystem services and human well-being: a case study in Huailai County, China. Environ Earth Sci 75, 416.

Amacher, M.C., O'Neill, K.P., 2004. Assessing soil compaction on Forest Inventory & Analysis phase 3 field plots using a pocket penetrometer (No. RMRS-RP-46). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Potgieter, L., Gaertner, M., Kueffer, C., Larson, B., Livingstone, S., O'Farrell, P., Richardson, D., 2017. Alien plants as mediators of ecosystem services and disservices in urban systems: a global review. Biological Invasions 19, 3571–3588

Vahdati, F.B., Mehrvarz, S.S., Dey, D.C., Naqinezhad, A., 2017. Environmental factors-ecological species group relationships in the Surash lowland-mountain forests in northern Iran. Nordic Journal of Botany 35, 240–250.

Appendix: Plant species

Herbs

Plantago lanceolata

Hypochaeris radicata

Richardia brasiliensis

Sida dregei

Trifolium repens

Pseudognaphalium luteoalbum

Bidens pilosa

conyza bonariensis

Verbena tenuisecta

Chenopodium album

Angemone ochroleuca

Convolvulus sagittatus

Malva parviflora

Hermannia umbratica

Sida ternata

Rapistrum rugosum

Cirsium arvense

Nasturtium officinale

Taraxacum officinale

Sonchus Integrifolium

Lepidium africanum

Sonchus asper

Hirsuta crabbea

Conysa chilensis

Sonchus oleraceus

Paronychia brasiliana

Tagetes minuta

Asparagus officinalis

Verbena bonariensis

Cirsium vulgare

Verbena brasiliensis

Sonchus integrifolia

Grass

Aristida congesta subsp. Congesta

Pennisetum clandestinum

Sporobolus festivus

Bromus catharticus

Trees

Acacia mearnsii

Europaea africana

Eucalyptus

Buddleja salviifolia