THE IMPACT OF SINKHOLES ON SPECIES RICHNESS AND DIVERSITY: IMPLICATIONS FOR MINE REHABILITATION.

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A research report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

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DECLARATION

I, Bronwen May Keiller, declare that this research report is my own, unaided work unless specifically acknowledged in the text. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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(Signature of candidate)

26 day of July, 2010

ABSTRACT

Mining often results in numerous detrimental impacts on the surrounding environment. One such potential impact is the formation of sinkholes on mining property, commonly resulting from dewatering operations initiated by mines to keep working conditions dry and safe. The rehabilitation of these sinkholes poses problems for mines that near closure; not only because of the potential costs involved, but also in determining the best methods to rehabilitate a sinkhole.

In order to determine the best rehabilitation requirements the differences in biodiversity found between sinkholes and the surrounding area were examined. Two sinkholes and the areas surrounding each sinkhole were sampled for small mammals, reptiles, amphibians, invertebrates. Basic vegetation and environmental variables studies were also conducted.

Grass cover was significantly higher than all other environmental variables (woody, forbs, rock, bare ground and plant litter cover) outside the sinkhole. Inside the sinkholes plant litter, grass and rock cover were significantly higher than the other environmental variables. Woody cover was significantly higher inside the sinkholes, compared to woody cover outside the sinkholes. The average percentage cover of broad-leaved plants was significantly lower than narrow-leaved plants outside the sinkholes. The cover of broad leaved plants outside the sinkholes was significantly lower in comparison to cover inside the sinkholes. No significant differences were recorded between different seed dispersal types outside the sinkholes. However, inside the sinkholes, the average percentage cover of plants with other types of seed dispersal was significantly higher than animal dispersed seed types. The floral composition analyses found that *Tagetes minuta* featured prominently inside the sinkholes, while *Digitaria longiflora* was the most important species outside the sinkhole. The multivariate analysis showed a certain degree of separation between inside and outside quadrats, based on the environmental variables studied. A total of six animal classes were recorded in the study sites. Insecta were most abundant both outside and inside the sinkholes. Outside the sinkholes, Insecta were significantly higher than Arachnida and Myriapoda. Amphibians were significantly lower than all other animal classes. Inside the sinkholes, Insecta and Arachnida were significantly higher than Mammalia and Reptilia.

The sinkholes examined in this study do not appear to have decreased levels of biodiversity, but rather present altered environmental conditions to those found outside the sinkholes, allowing the establishment of different species. The exclusion of fire, grazing and frost from sinkholes are likely to be contributing factors in the different growth type abundances and may also impact on invertebrate abundances. The environmental conditions inside the sinkhole that differ from surrounding conditions may be preferred by certain species, while they are avoided by others. Faunal species appear to exhibit individual preferences on sinkhole selection based on their life strategies. Given sufficient time it would appear that sinkholes regenerate to sufficient levels that allow ecosystem functioning. As a result of this, it may not be necessary to refill sinkholes unless out of safety concerns.

Only a limited number of variables were examined in this study and future work is required to justify the findings and explanations given herein. Additional environmental variables, such as slope, and detailed studies on the exact differences in moisture, humidity, sunlight, temperature etc. between the sinkholes and surrounding areas should be included in further studies. Both the grazing and burning regimes of the sinkholes and surrounding areas should be established to provide further insight and understanding in the differences between sinkholes and the surrounding areas.

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1. GENERAL INTRODUCTION

1.1 Biological Diversity

As the human population has and continues to impact on the environment, at both local and global scales, the value of biodiversity and its role in ecosystem functioning has been the focus of much ecological research, with an explosion of research over recent years (Hooper *et al*., 2005). Many definitions of biodiversity (or biological diversity) exist in the literature, and so I follow DeLong's (1996) review in which he defines biodiversity as an attribute of a particular area that consists of the variety within and among the biotic communities, whether influenced by humans or not, at any spatial scale from microsites and habitat patches to the entire biosphere. Biodiversity thus includes all life forms, from the range of species to the different races and populations of each species, together with the ecosystems and their ecological processes (Myers, 1996).

Biodiversity is considered to include three primary attributes of ecosystems: composition, structure and function. These three spheres are interconnected and interdependent, with no single level of organisation being fundamental and different levels of resolution being appropriate for different questions (Noss, 1990). When assessing biodiversity, the effects of environmental stresses will be expressed in different ways at different levels of biological organisation. An interest in biodiversity represents an opportunity to address environmental problems holistically, rather than in the traditional and disconnected species-by-species, stress-by-stress fashion (Noss, 1990).

Two of the major components of diversity are species richness and species abundance (Magurran, 1988; Noss, 1990). Investigations are often restricted to species richness (a straightforward count of species present), but regarding species as being equally represented in different areas is insufficient. We often want to know more about the species present, such as commonness or rarity (Humphries *et al*., 1995). No community consists of species of equal abundance, rather a few species would be very abundant, some would have medium abundance and most would be represented by only a few individuals (Magurran, 1988). In addition to the number of species within an area, it is also important to know how individuals are distributed within it (Humphries *et al*., 1995). Species richness and diversity are often used in the assessment of ecosystem fitness and for conservation purposes (Burel *et al*., 1998). Species density (number of species per m^2) is a commonly used measure of species richness (Magurran, 1988; Lévêque, 1997).

1.2 The Value of Biodiversity

Much debate exists as to the ecological value of diversity, but it is recognised as playing two critical roles in ecosystem services: it provides the biospheric medium for energy and material flows, which in turn provide ecosystems with their functional properties, and it supports and fosters ecosystem resilience. The resilience of an ecosystem relates to its ability to resist stress, absorb disturbance and recover from disruptive change, much of which can be attributed to human activity (Myers, 1996). This would suggest that in environments surrounded by mining operations, for example, it is imperative to ensure that the ecosystem is as diverse as possible, thus enabling it to recover from the detrimental effects resulting from mining operations. Mining companies are made increasingly aware of this, through government regulations and non-governmental organisations, and are becoming more active in the conservation of biodiversity (Gold Fields, 2006).

Contrasting views exist as to the value of biodiversity in fostering ecosystem resilience. For instance, the diversity-stability hypothesis states that species differ in their traits, and thus more diverse ecosystems are more likely to contain some species that can survive certain environmental stresses, thereby compensating for competitors that are reduced by that disturbance (Lawton and Brown, 1993; Tilman and Downing, 1994). This hypothesis predicts that biodiversity should promote resistance to disturbance. In contrast, the species-redundancy hypothesis argues that many species are so similar that ecosystem functioning is independent of species richness, as long as the major functional groups (producers, consumers, decomposers etc.) are present (Lawton and Brown, 1993; Tilman and Downing, 1994).

The structure of biological communities is often influenced by natural disturbances. The gaps created by fires, storms and even the activities of burrowing animals can alter species abundances, modify the physical environment and create opportunities for regeneration, with strong consequences for community composition and biological diversity (Kotanen, 1996).

Succession refers to the changes observed in an ecological community following a disturbance that results in relatively large open space (Connell and Slatyer, 1977). The established view of succession is that following a disturbance, several assemblages of species progressively occupy a site, each giving way to a successor until a community develops that is able to reproduce itself indefinitely. Each suite of species modifies the site conditions so they become less suitable for its own existence and more suitable for its successor. Eventually a final community exists at equilibrium with the established environment (Noble and Slatyer, 1980).

Not all disturbances necessarily result in reduced biodiversity. The occurrence of a fire, for example, undoubtedly ‘disturbs’ an ecosystem and yet, it is an important part of African savannas and plays a vital role in determining the composition and structure of these ecosystems. Fire is often used as one explanatory factor in the coexistence of trees and grasses in savannas (Govender *et al.*, 2006). Without fire, considerable areas of savanna could develop into closed woodlands, excluding otherwise potentially valuable species. Fires also occur frequently in grasslands and can extend through several kilometres, without causing any change in community composition (Turner *et al.*, 1998).

Another hypothesis, the intermediate-disturbance hypothesis, predicts that species richness is highest at levels of intermediate disturbance. However, studies have shown that this disturbance-diversity relationship can be positive or negative, depending on other contributing factors. For example, plant species richness was found to increase under higher levels of grazing in a nutrient rich environment, whereas in a nutrient poor environment, higher levels of grazing resulted in decreased plant species richness. This implies that the level of disturbance that maximises species richness depends on productivity (Kondoh, 2001).

Numerous hypotheses exist to explain, understand and predict how ecosystems react in response to various disturbances. Biodiversity undoubtedly contributes to ecosystem functioning and is influenced by a variety of environmental factors. Through the continual study of how ecosystems respond to disturbances we can further understand the role that biodiversity plays in the resilience of an ecosystem.

1.3 Biodiversity and Mining

1.3.1 Sinkholes

South Africa is a country blessed with vast mineral reserves and mining plays a major role in the economy. Mining has numerous impacts on the environment; the most common being the negative impacts on biodiversity as a result of the increased pressure placed on the natural resources that surround mining operations (Gold Fields, 2006). The formation of sinkholes on mining properties and neighbouring areas poses yet another threat to the biodiversity found in such mining areas.

Sinkholes, in general, are roughly conical or cylindrical in shape, varying in depth (from 1 – 50 m), with a diameter of up to 100 m (or larger) and can be dangerous as they occur without warning and in a matter of seconds (Foose, 1967; Brink, 1979). Sinkholes develop due to a sudden collapse of overburden into a mine opening or cavity and result in an abrupt depression of the local ground surface (Singh and Dhar, 1997). The sudden formation of sinkholes can be catastrophic (Foose, 1967) and may result in costly damage and even loss of life, for example when they develop beneath highways, railroads, buildings, dams and pipelines (Newton, 1984; Gutiérrez *et al.*, 2008). The main factors leading to sinkhole formation include shallow depth of cover, weak overburden, geological discontinuities and dissolution of rocks (Singh and Dhar, 1997). Sinkholes can be separated into two categories, induced and natural, even though the processes involved in their occurrence are the same. Induced sinkholes differ from naturally forming sinkholes in that they are caused or accelerated by man's activities, while natural sinkholes are not (Newton, 1984; Gutiérrez *et al.*, 2008).

A vast majority of active sinkholes are considered to be caused or accelerated by human activity (Waltham *et al.*, 2005). Induced sinkholes can further be separated into two types; those resulting from a decline in water level, usually as a result of dewatering programmes (the lowering of the water table to keep underground mining operations dry and safe), and those occurring as a result of construction activities (Newton and Tanner, 1987). The lowering of the water table, in particular, has been specifically linked to sinkhole development (Newton, 1984; Swart *et* al., 2003a), possibly resulting from the removal of hydrostatic support to the overlying layers (Singh and Dhar, 1997). The occurrence of sinkholes can also be aggravated by rainfall and earthquakes (Singh and Dhar, 1997), though these would be considered as natural contributors.

The Far West Rand gold-mining district, approximately 65 km west of Johannesburg, South Africa, is overlain by a layer of dolomite and dolomitic limestone between 900 and 1000 m thick. All mining on the Far West Rand must extend through this thick carbonate section (Foose, 1967). Dolomite in general and particularly the Transvaal dolomite has a notorious reputation for causing instability, as weathering and erosion cause a natural instability of dolomitic rocks, with sinkholes being formed continuously. Given sufficient time and the correct triggering mechanisms, ground instability on dolomite land occurs naturally, but is greatly accelerated by human actions, such as lowering of the water table. Unfortunately, dewatering of the dolomitic ground water compartments in the Far West Rand is a necessity to keep workings 'dry' and provide mine workers with a safe working environment (van Niekerk and van der Walt, 2006).

Two main situations exist for sinkhole development; the first relates to surface subsidence, whereby solution sinkholes form as a result of corrosional lowering of the ground (the formation of a sinkhole by above ground sources, for example, erosion). In contrast, the second type results from the subsurface dissolution and the downward movement of overlying material. These are the most important from a ground instability and engineering perspective (Gutiérrez *et al*., 2008) and form the basis for this study.

The formation of sinkholes, in the Far West Rand in particular, can be attributed to the declining groundwater levels, as a result of the dewatering programs initiated by mines in the area (Foose, 1967; Swart *et al*., 2003a). While it is generally accepted that sinkhole formation can be attributed to water table fluctuations, the explanations of how groundwater activities affect sinkhole development are controversial (Daoxian, 1987). Foose (1967) gives one explanation; the combination of the ease of water movement through the dolomites with the uniform gradient of the groundwater surface indicates an almost continuous network of interconnected solution cavities within the dolomites. As the groundwater surface is lowered in an area of weathering, volume shrinkage due to compaction of the unconsolidated debris takes place and an opening may develop. Dewatering of the unconsolidated debris causes downward migration of debris into the existing openings, widened by solutions. Flushing of this material serves to further open space within the bedrock into which additional material can move. The cavern gradually grows upwards, enlarging the roof, eventually exceeding the lithostatic load that can be supported. At that point, rapid upward spread results in the sudden collapse of the surface, forming a sinkhole (refer to Figure 1). Lowering of the groundwater table initiates compaction, with resulting land subsidence and development of debris caverns, and consequent collapse of the surface (Foose, 1967).

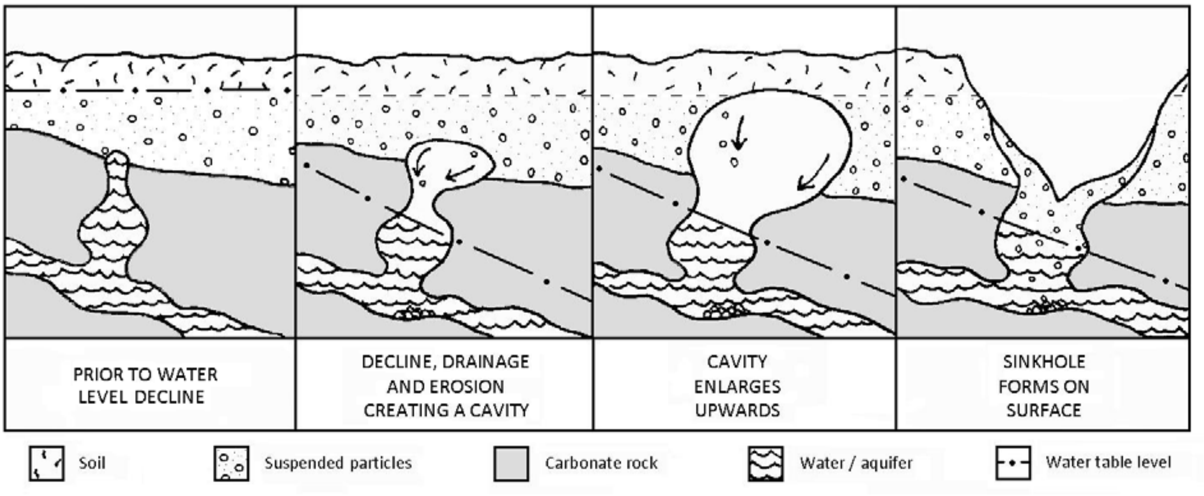

Figure 1: Sinkhole formation (modified from Newton and Tanner, 1987)

Caves form naturally in dolomite or limestone because carbonate minerals dissolve easily in slightly acidic groundwater, leaving vast underground chambers lined with stalactites, stalagmites and other cave deposits. When such underground caves manifest themselves on the surface, they can form sinkholes with disastrous consequences, as in the 1960s in Carletonville in Gauteng, South Africa (Cairncross, 2004).

1.3.2 Rehabilitation of Sinkholes

The Department of Minerals and Energy (1998) requires the implementation of effective and affordable measures and environmental impact management standards, the prevention or efficient management of water, soil and atmospheric pollution and the rehabilitation of areas affected by past mining operations. Following growing global environmental awareness and concern, combined with legal requirements, more mining companies are seriously committed to minimising and mitigating environmental impacts. Following the loss of life in earlier sinkhole formations, the Far West Rand Dolomitic Water Association was founded in 1964 to manage problems associated with de-watering, including the risk of sinkhole formation, and protect human safety (Swart *et al.*, 2003b; Gold Fields, 2006). Biodiversity is also an important issue and the Karst Management Committee was founded in 2005 to protect endangered bat species found in caves on the property (Gold Fields, 2006).

After more than 70 years of gold mining on the Far West Rand, some gold mines are reaching the end of their economic viability and will close down (van Niekerk and van der Walt, 2006). Before a closure certificate can be issued by government, it is necessary for the relevant mining operations to sufficiently rehabilitate the land to pre-mining conditions (Reichardt, 2008). The Minerals and Petroleum Resources Development Act (MPRDA) 28 of 2002 states in Section 38 that (1) the holder of a reconnaissance permission, prospecting right, mining right, mining permit or retention permit (d) must as far as it is reasonably practicable, rehabilitate the environment affected by the prospecting or mining operations to its natural or predetermined state or to a land use which conforms to the generally accepted principle of sustainable development. Further

(e) is responsible for any environmental damage, pollution, or ecological degradation as a result of his or her reconnaissance prospecting or mining operations and which may occur inside or outside the boundaries of the area to which such right, permit or permission relates (MPRDA, 2002). For companies with sinkholes on their properties, this is a daunting, if not impossible, task. Rehabilitation of sinkholes usually focuses on filling the void left by the sinkhole (Garlanger, 1984). However, as several of the sinkholes that have formed on mining property posed no immediate threat to infrastructure or human life, they were left untouched. The difficulty arises in determining how best to rehabilitate such sinkholes, some of which are massive (125 m in diameter and 50 m in depth). Would it be better to fill the sinkhole or, after 50 odd years of recovery, has the sinkhole naturally rehabilitated and recovered sufficiently to warrant its preservation?

While the most common method (as well as the cheapest and easiest) of rehabilitating a sinkhole is to simply fill the void with whatever material is available, this is seldom stable in the long term and several examples exist where re-filled sinkholes appear to be stable, but begin to subside again after periods of high rainfall (Swart *et al.*, 2003 a; Waltham *et al.*, 2005).

There are two basic alternatives in sinkhole remediation; to completely seal the outlet conduit at its base or to fill it with enough graded material, which will remain stable when storm water drains through it (Waltham *et al.*, 2005). The first option requires the throat (the opening of the sinkhole to the subsurface) of the sinkhole to be sealed with concrete plugs or capped with reinforced concrete where it enters the bedrock. An ongoing hazard resulting from this method is the risk of a new sinkhole forming from the diverted infiltration flows. Sinkhole remediation that does not consider drainage is likely to require further repair (Waltham *et al.*, 2005).

An additional potential risk may arise from the type of material that is used to fill the sinkhole, agricultural and industrial waste could result in contamination of local wells. Sinkholes are pathways for contaminants to enter an aquifer and may adversely affect groundwater quality. Remediation of groundwater is virtually impossible (Waltham *et al.*, 2005). Karst aquifers are also particularly vulnerable to pollution because their underground conduits provide no filtration (Daoxian, 1987).

More attention is given to the current management practices of sinkholes in Chapter Two of this report.

1.3.3 Sinkholes and Microhabitat

It is well known that organisms occupying the same general area may experience very different physical conditions. A macrohabitat is the area in which individuals perform all their biological functions, while the microhabitat is composed of the environmental variables that affect individual behaviour (Jorgensen, 2004). For example, the microclimate (the climate experienced in a small, specific area) experienced by an individual can vary markedly from the regional climate, often tending to be more stable than that of the surrounding macrohabitat climate (Cloudsley-Thompson, 1975; Bennie *et al.*, 2008). This may have important implications for lizard and small mammal species that choose microhabitats based on their ability to facilitate thermoregulation, with the presence of suitable burrows or basking spots (Adolph, 1990).

The formation of a sinkhole creates the foundation for a new ecosystem that is different from the surrounding environment. A sinkhole provides a cool, damp environment that may allow atypical species to establish themselves (Friend, 2002). Thus, in theory, sinkholes could form microhabitats that differ from the surrounding area, with regards to several environmental factors that may affect the distribution and abundance of species found within the sinkhole. For example, the calcium-rich walls of a sinkhole attract plants that require an alkaline environment to survive. Additionally, the continuous moisture of an old, stable sinkhole will attract plants that thrive in damp and humid conditions, such as mosses and ferns (Friend, 2002).

There are numerous factors that affect and contribute to microclimates. At mid to high latitudes, the slope and aspect of ground alters the amount of solar radiation received by the surface and can be an important factor in determining the ecological conditions at a site. Complex topography may provide refugia and solar microclimates that allow populations to persist beyond the range that would otherwise be possible (Bennie *et al.*, 2008). The difference in topography from the sinkhole to the surrounding area may provide microhabitats that are preferred by populations in the area. Additionally, topography can result in increased wind protection and in the production of eddies and turbulence immediately behind the barrier that destroys normal laminar flow. The climate of the air above the ground depends both upon the proximity and the nature of the surface. The nature of the soil surface has a great influence on the amount of heat required to bring about a change in temperature and there have been remarkable recorded differences between air temperature and surface temperatures. Microclimate conditions can also be influenced by humidity, wind speed and other physical conditions that affect the lives of animals and plants (Cloudsley-Thompson, 1975).

Little work has focused on the levels of diversity found within sinkholes following their formation. The majority of studies concerning sinkholes that I have come across are concerned with the sinkhole's impact on infrastructure, groundwater pollution, remedial engineering, and the prediction and evaluation of sinkhole-susceptibility (Beck, 1984). Internet searches revealed only brief mentions of the increased biodiversity resulting from a pond that formed in a sinkhole and the possibility of altered biodiversity as a result of the cooler and moist conditions that may be found within a sinkhole (Friend, 2002). As far as can be established, very little mention has been given to the difference in species richness and abundance found within sinkholes.

Despite thorough literature research, little to no information was found detailing the environmental differences found between sinkholes and their surrounding environment. The purpose of this study was to determine if any such difference does exist. Further to this, no studies specific to South Africa were found that examine sinkhole biodiversity. As such, this study was designed as a baseline study to determine any fundamental differences between sinkholes and their surrounding environment. Following this, additional studies could be initiated to determine what threat sinkholes and their species assemblage may pose to surrounding grasslands.

This study aims to investigate and compare the species richness and abundance found between two sinkholes and their surrounding area, thus evaluating differences in biodiversity between the two environments and determining whether the biodiversity found within the sinkhole differs significantly from the surrounding area. This study will form part of a long term study and provides the basis for further study in this field. This will allow recommendations to be made to the relevant mining authorities on whether sinkholes are valuable in terms of biodiversity and conservation value and any potential rehabilitation requirements prior to mine closure.

2. CURRENT SINKHOLE MANAGEMENT

A sinkhole is not merely a hole in the ground. It has hydrological and geological significance. Within the karst[1] environment, a sinkhole usually develops as a drainage point into a subsurface water system, where they act as funnels, directing surface stormwater runoff from the ground surface into karst aquifers (Zhou and Beck, 2005 and 2008). These water systems can thus also transmit any suspended sediment carried by the turbulent flow and materials resulting from human activities, including contaminants. These contaminants may end up in caves, springs and water wells in the area of the sinkhole (Zhou and Beck, 2008). Thus, the management and remediation of sinkholes is considered vitally important, not only for the protection of above ground infrastructure, but also to protect underground resources, such as groundwater. This is particularly important in areas where sinkholes may be exposed to external contaminants, such as when they form near urban areas or infrastructure. The sinkholes surveyed in this study formed on agricultural land owned by a mining company. As such, no remediatory work was carried out, possibly as a result of the low risk environment surrounding the sinkholes (no nearby infrastructure or contaminants).

With closure inevitable for mines, the environmental impacts of mining on what may have been previously productive land require serious consideration. The probable impacts should be evaluated so that planning can focus on future challenges involving re-watering. For example, based on the monitoring of sinkhole activity in the Lower Wonderfontein Spruit region, recommendations were made that proposed no community development in the streambed area, as even filled sinkholes remain susceptible to reactivation (Swart *et al.*, 2003 b). This may have serious implications for the mining company that owns the property, as the land remains the responsibility of the mine until it has been sufficiently rehabilitated and can be used for other purposes.

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[1] Surface topography formed over limestone and/or dolomites, characterised by depressions and sinkholes formed by the dissolution of carbonate rock (Cairncross, 2004).

Sinkholes form throughout the world and the resultant problems they cause are similar the world over, as a result much information exists on the ways to best mitigate and prevent the future formation of sinkholes. Here we discuss the different methods used in sinkhole remediation, through case studies, to highlight the difficulties faced in the rehabilitation of sinkholes.

2.1 Remediation of sinkholes

Sinkhole remediation refers to the process involving the repair of existing sinkholes and the prevention of their future reactivation (Zhou and Beck, 2008). Abundant literature exists on the remediation of sinkholes and generally follows similar principles of remediation. The majority of sinkholes that receive remediation are those that form in already developed areas and as such, require mitigation action to prevent further damage to property and infrastructure, as well as to improve safety. It is generally accepted that facilities should not be developed within an already formed sinkhole due to concerns of flooding, future collapses and potential impact on groundwater (Zhou and Beck, 2008).

Two basic options exist for sinkhole remediation: the first is to simply fill the sinkhole with enough graded material so that it will remain stable when stormwater drains through it, or secondly to completely seal the sinkhole throat at its base (Waltham *et al.*, 2005).

2.1.1 Case studies

Case Study # 1: Wonderfontein Valley, South Africa (Swart et al., 2003 b)

Dewatering of the Oberholzer Compartment, in the Wonderfontein Valley, was initiated in the mid-1950s. By 1984, 21 sinkholes had formed in the area. Dewatering of the Bank Compartment initiated in 1969 resulted in the first sinkhole forming in 1970. A total of 208 sinkholes had formed by 1984. By the mid-1980's the mining company decided to rehabilitate sections of the Lower Wonderfontein Spruit that crossed the dewatered compartments. A survey revealed a total of 271 sinkholes in the Wonderfontein Spruit, with a total volume of 2 450 000 m^3 and an average volume of 9 000 m^3 per sinkhole.

In 1987 all sinkholes within 100 m from the streambed centre were filled with compacted material. Sinkholes further than 100 m away from the streambed had diversion beams built around them to prevent stormwater draining into them. Sinkholes that were some distance from active mining operations (80 %) were backfilled with soil from nearby borrow pits and revegetated from seed mixtures of various indigenous grasses. Sinkholes in the immediate vicinity of mine operations (20 %) were backfilled with a mixture of mine tailings and waste rock, capped with fertile soil and seeded for vegetation growth.

The backfilled sinkholes were surveyed in 1993 and after a period of six years, 72 sinkholes had redeveloped. The majority of these were considered to be consolidation of backfilled material and only a few new sinkholes had formed. In 1995 a comprehensive refill and top-up operation was initiated.

However, in 1997, following periods of intense rainfall and storm flow, 231 sinkholes formed in the Spruit region since the rehabilitation in 1995. This was likely due to the fact that the tailings used to fill certain sinkholes contained large amounts of water and upon drying out, the material shrinks and develops large cracks. Water then runs through these cracks into the throats of backfilled sinkholes, eventually causing the sinkholes to reactivate. In cases where the sinkholes were well plugged, no reactivation occurred.

Although, the methods used were considered to be the most cost-effective, the costs of rehabilitating the sinkholes amounted to millions of US dollars.

Case study # 2: The Macungie Sinkhole, Pennsylvania (Dougherty and Perlow, 1987)

A sinkhole collapse, measuring 30.48 m in diameter and 12.19 m deep, developed suddenly underneath a street in Macungie Village, Lehigh Valley, Pennsylvania. Fortunately, no one was injured and damage was confined to the street, parking lots, sidewalks, sewer lines, water lines and utilities. Further expansion of the sinkhole posed threats to more than 17 residences adjacent to the sinkhole.

Investigations were conducted to determine if there was any history of sinkhole activity at the site. This included conducting interviews with residents and analysis of air photos. In addition, a subsurface investigation program was initiated, which included test borings, air track drilling, terrain conductivity and electrical resistivity geophysical surveys. Results of these investigations revealed that the sinkhole formed in the northern half of an old filled-in sinkhole, estimated to be 38.1 to 76 m in size. The un-collapsed portion of the sinkhole was undergoing slow but perceptible movement into the collapsed area. Based on previous experience, a rock and concrete plug was adopted as the primary stabilisation method.

All collapsed soils and fill material were removed from the zone of immediate collapse and large dolomite boulders were systematically placed and knitted together with concrete. A conical shaped plug was constructed and seated into firm stable ground on three sides of the sinkhole. A reinforced flexible concrete mat was constructed over the sinkhole collapse area to distribute overburden loads should any portion of the underlying rock tend to locally settle. The concrete mat and plug were then covered with compacted clay fill. Backfilling operations proceeded for 25 working days and required placement of 8000 cubic yards of soil to restore the roadway and parking areas. Roadway and utility construction proceeded afterwards.

Stabilisation and repair costs totalled some US$ 450 000 and almost three months were required to restore utility services, roadway and parking areas.

Case study # 3: Keystone Heights Sinkhole, Florida (Gordon, 1987)

A sinkhole collapse occurred beneath an existing house in Keystone Heights, Florida. The sinkhole measured 15 m in diameter and 14 m in depth and completely swallowed the house.

Soil test borings were performed on opposite sides of the sinkhole and revealed various voids from a depth of 15.5 to 23.5 m. Engineering recommendations were made to the owners, but economic constraints determined the extent of the remedial work.

Recommendations included:

- Cleaning out existing debris to reduce voids in the fill material and enable penetration of grout pipes
- Capping the top and bottom of the hole with a clay backfill to provide a water barrier between the lime rock and overburden
- Digging interception ditches along the uphill side of the sinkhole to divert surface runoff
- Monitoring settlement after filling has been completed
- Performing a geophysical survey to determine the extent of the cavity
- Grouting the sinkhole throat to plug the breach in the bedrock surface.

Instead of removing all debris, some attempt was made to burn the wooden garage of the house inside the sinkhole. Fill was placed as recommended. Railway ties were used as substitutes for interception ditches to divert surface runoff.

The sinkhole appears to have remained stable after remediation. The total cost of repairs, including engineering services, amounted to less than US$14 000.

Case study # 4: Mann Road sinkhole, Florida (Goehring and Sayed, 1989)

A sinkhole developed suddenly beneath an effluent transfer line in Orange County, Florida. The sinkhole eventually measured 15 m in diameter and 6 m deep.

To prevent the undermining of the pipeline, immediate actions were necessary. The sinkhole was immediately filled with sandy soil to provide support for the pipeline. A program of deep subsoil stabilisation was recommended to densify soil conditions and prevent future soil erosion. The program consisted of pumping cementaceous grout at various locations in the sinkhole. A total of ten cement injections were made in the depth interval of 38 to 60 m.

Following the grouting program, three standard penetration test (SPF) borings and two auger borings were drilled. This was to determine post-grouting water levels and to install monitoring wells. The deep conditions in this site were found to improve significantly as a result of cement-grouting.

While the cement grouting proved to stabilise the deep subsoil conditions, further remedial action would be required due to consolidation of near surface material. Improvement of the shallow soil conditions would be necessary to provide adequate support for the pipeline. This could be achieved by additional shallow grouting and/or implementation of a foundation system.

2.1.2 Recommendations

For successful remediation, a thorough geotechnical study should be performed so as to understand how the sinkhole formed. The characteristics of the sinkhole and the intended use of the sinkhole site should then determine the mitigation approach. All engineering measures need to be tailored to suit the unique geologic and hydrologic characteristics of each sinkhole. Successful sinkhole mitigation should include plugging of the sinkhole throat, filling the sinkhole body and construction of a sinkhole cap (Zhou and Beck, 2008).

Sinkhole throats should be sealed with concrete plugs or capped with reinforced concrete where they enter the bedrock. Once the drainage outlet is sealed, the material used to fill the sinkhole is not critical and the only potential hazard is the possibility of new sinkholes forming as a result of the diverted infiltration flows (Waltham *et al.*, 2005).

The safest mitigation strategy is to simply avoid the subsidence features and areas most susceptible to sinkhole development. This would be best applied through the prohibition and limitation of development in the most hazardous areas through land use planning and regulations, which is commonly most effective when developed by the local administration (Gutiérrez *et al.*, 2008). In mining areas, where dewatering is a necessity, this may not be a feasible option, but should be considered during mine closure and during the rehabilitation of affected areas. Safe mitigation generally requires careful planning and the application of subsidence protected engineering designs, as control of subsurface dissolution and the processes involved in the generation of sinkholes may be difficult (Gutiérrez *et al.*, 2008).

Milanovic (2000) recommends the following corrective measures aimed at diminishing the activity of the processes:

- Prevent water withdrawal and water table decline
- Line canals and ditches
- Use flexible pipes with telescopic joints
- Control irrigation
- Make the surface impermeable with geomembranes / geotextiles
- Use efficient drainage systems and divert surface runoff away from problem areas
- Remediate sinkholes and clog shallow holes
- Fill cavities in the soil or rock by grouting
- Improve ground compaction or inject grouting to increase the strength and bearing capacity of the soils
- Construct cutoff screens and grout curtains beneath dams to avoid ground water circulation beneath structures.

When sinkhole-prone areas are occupied by people, vulnerable buildings and/or infrastructure, the sinkhole risk should be mitigated by reducing the activity and severity of the processes (causing sinkhole development), the vulnerability of buildings or both. When sinkholes form in developed areas, different types of engineering measures have been applied or proposed to protect structures from sinkhole development (Gutiérrez *et al.*, 2008).

These include:

- Special foundations for buildings
- Reinforce linear infrastructure (roads, railways etc.) by incorporating tensile geogrids in the sub-base and embankments
- Rigid structures, such as reinforced concrete slabs, which can act as ground bridges to protect high-speed railways that will not tolerate even slight settlement

- Sinkhole resistant bridges that can be built to incorporate oversized foundation pads.

According to Gutiérrez *et al*. (2008), additional non-structural measures should be considered, which would aim at reducing financial losses and harm to people, such as:

- Insurance policies to spread the cost generated by sinkholes among the people at risk
- Monitoring in problematic areas with highly vulnerable structures
- Educational programs aimed to adequate the perception of the hazard among the public and decision makers to the objective likelihood of sinkhole occurrence
- Erecting fences and warning signs of sinkholes and sinkhole prone areas

Selected best management practices over sinkholes include the following (Zhou and Beck, 2008):

- Brief on-site personnel on the special protective measures recommended for sinkholes and the safety concerns associated with operating within and around them.
- Cease operating activities, if previously unidentified sinkholes are encountered during construction, until the feature is properly assessed.
- Avoid excavation activities during storm events or periods of sustained heavy rainfall to reduce the potential for soil erosion and sediment transport into the subsurface.
- Maintain natural surface drainage pattern as much as possible to avoid disrupting natural subsurface flow.
- Pile any surplus surface materials away from the sinkholes.
- Minimise clearing of vegetation within sinkholes as much as possible to provide suitable areas for infiltration of surface runoff.
- Use controlled blasting techniques to minimise the vibration and sound waves.
- Avoid fuelling or servicing machinery near sinkholes.
- Conduct a geophysical investigation to understand the subsurface conditions and identify any buried sinkholes in areas where sinkholes are a common occurrence,.

- Document all information regarding the sinkhole including dimensions, shape, drainage area, swallet (the sinkhole throat) information and type.
- Design erosion and sediment control and stormwater management facilities so that the excavated materials do not drain into the sinkholes.
- Design a filtering system to prevent lateral erosion while allowing water to pass. This would depend on whether the sinkhole needs to continue accepting some or as much water as in the past. The size of the tributary drainage area, the runoff water quality and the difficulty of establishing an alternate outlet would influence this recommendation.
- If the sinkhole may undermine the safety of the construction site, the sinkhole should be remediated appropriately or engineering measures should be taken to ensure that the facility remains undamaged.
- Keep the wheels or tracks of ground-based machinery away from the edge of the sinkholes for safety of the operators.
- Whenever uncertainties arise, always work with a qualified geologist to develop specific best management plans for each sinkhole.

In general, stormwater runoff management constitutes the most important part of sinkhole management plans on karst lands.

The safest mitigation strategy is the avoidance of subsidence features and the areas most susceptible to sinkhole formation (Gutiérrez *et al.*, 2008). However, this is not always possible and the processes involved in sinkhole remediation are complex and costly. The option of simply filling a sinkhole with the most easily available material very seldom provides a stable solution in the long term (Waltham *et al.* 2005).

3. MATERIALS AND METHODS

3.1 Study Sites

Fieldwork was conducted on properties owned by the mining company Goldfields, located outside Carletonville, approximately 70 km west of Johannesburg, South Africa (Figure 2). The area experiences summer rainfall between November and April, with an average of more than 640 mm per annum. The mean maximum monthly temperature of Carletonville is usually higher than 27˚C from October through to January, dropping to a mean minimum of 3˚C during May to September (SAWB, 2009). The terrain lies mostly between 1372 – 1676 m above sea level, with hilly and rocky land that is typical of the Grassland Biome (Rutherford and Westfall, 1994, Cilliers *et al.*, 1999). In areas with a mean annual rainfall above 625 mm, sour grasses tend to predominate. The number of rare plants is not particularly high, but increases in the wetter areas and mainly includes non-graminoid plants (Rutherford and Westfall, 1994).

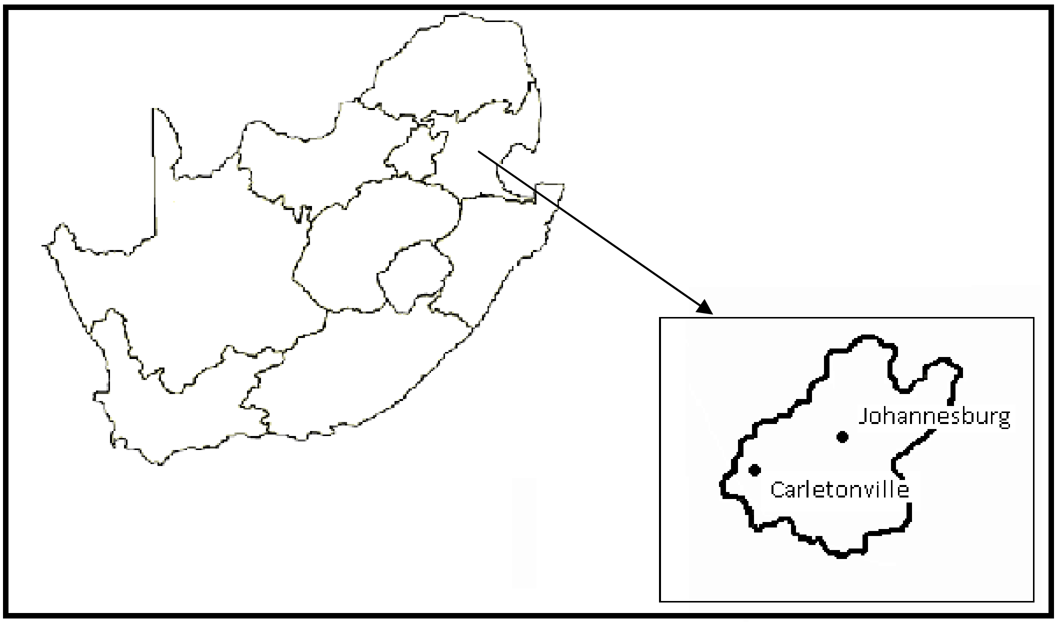

Figure 2: Locality map showing Carletonville relative to Johannesburg, South Africa

Carletonville, more specifically, forms part of the Carletonville Dolomite Grassland as described by Mucina *et al.* (2006). This type of grassland is found mainly in the North West and Gauteng and extends slightly into the Free State, in the region of the Potchefstroom, Carletonville and Ventersdorp. The vegetation and landscape features gently undulating plains, dissected by prominent rocky chert ridges. Species rich grasslands form a complex mosaic pattern dominated by many species. The grassland biome is a fire prone ecosystem and hence, fire plays an important role in the maintenance of both its structural and textural patterns. Grazing also has a major influence on vegetation structure in grasslands, as well as species composition (Mucina *et al.,* 2006).

The grassland biome contains the greatest concentration of urban development in southern Africa and the urban population density is greater than any other biome (Rutherford and Westfall, 1994).

Numerous sinkholes, of various sizes, are found in the Carletonville area. However, the majority of these are located on either mining or private land and are difficult to gain permission for access. Additionally, sinkholes located in suitable areas may not be easily accessible on foot and present safety risks. Two suitable sinkholes were identified on Goldfield's property for investigation (Figure 3). Sampling was conducted over ten nights from the 18th to the 28th of November, 2008.

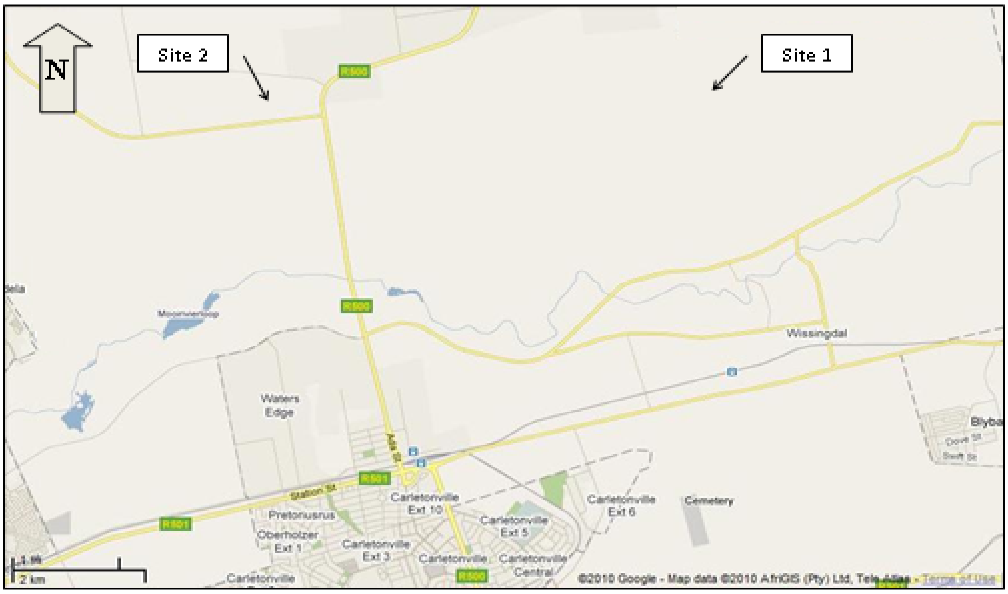

Figure 3: Map showing the relative position of sinkhole sites relative to nearby Carletonville, major roads and water courses © Google Maps.

3.1.1 Site 1

The first sinkhole (26˚ 17’ 19” S; 27˚ 24’ 54” E) identified as a suitable study site measured approximately 50 x 35 metres in diameter and is 8 m deep (Figure 4).

The sinkhole appears to be located next to a disused (limestone) quarry. The area surrounding the sinkhole consists of open grassland with scattered trees and rocks, which is used by local farmers for grazing cattle. The general topography of the area is flat, however small hills immediately surround the south-east portion of the sinkhole. The sloping sides of the sinkhole are relatively steep but access could be gained by walking down most of them. A cave is located at the base of the sinkhole. No visible water sources (springs, streams etc.) are located in the general vicinity or inside the sinkhole itself. The age of the sinkhole examined in this study was not known.

Figure 4: Aerial Image of Site 1 © Google Earth

3.1.2 Site 2

The second sinkhole (26˚ 17’ 27” S; 27˚ 22’ 17” E) is located 4 kilometres west of Site 1 and is part of a series of interconnected sinkholes of various depths and sizes (Figure 5). The particular sinkhole that was chosen as Site 2 was determined on the basis that it was the largest sinkhole with reasonably easy access. It measured approximately 30 x 15 metres in diameter and is 6 m deep.

The sinkhole cavities are located just next to a road, while Site 2 itself is approximately 100 m away from the road. The area immediately surrounding the sinkhole is predominately grassland, with a few scattered trees. The surrounding topography is flat, with small man-made soil ridges located approximately 500 m east and 100 m west of the sinkhole. The slopes into the sinkhole are steep with only one being suitable for access. There is a fair amount of rock scattered about the sinkhole and no water sources are located in the general area or inside the sinkhole. The age of the sinkhole examined was not known.

Figure 5 Aerial Image of Site 2 © Google Earth

3.2 Sampling Techniques – Environmental Variables and Flora

Vegetation sampling involved the placement of ten random 1 x 1 m quadrats along two transect lines, one inside and one outside each sinkhole for each site. For each quadrat the following variables were recorded: percentage rocky cover, percentage plant litter, percentage grass cover, percentage forb cover, percentage woody cover and percentage bare ground. Additionally, a list of species found within each quadrat was recorded with the number of individuals, percentage vegetation cover and plant height for each species. A species richness curve was plotted to ensure an adequate number of species were collected to provide a valid representation of each site. The area-based species richness curve is commonly recommended for the estimation of minimum required study plot size (see Whaley and Hardy, 2000; Rajan, 2002). Any additional species that were obviously visible were also recorded.

Where possible, plants were identified in the field, but where this was not possible, specimens (preferably with flowers or other identifying characteristics intact) were collected, pressed, and taken to the University of the Witwatersrand for identification with reference specimens in the H.E. Moss Herbarium. Species names and spelling are in accord with Germishuizen *et al.* (2006).

Plant species were classified according to growth type (woody, herbaceous, grassy or succulent), leaf type (broad-leaved or fine-leaved) and their seed dispersal type (wind, animal or other). These were then analysed for significant differences in cover between their positions (inside or outside) relative to the sinkholes.

In each site ten 1 x 1 m quadrats were surveyed both inside and outside the sinkholes. The floral compostion for the total of 40 quadrats was assessed for species found exclusively inside and outside the sinkholes respectively, as well as for the combined effect of all species in all quadrats.

The following were calculated:

- Frequency (the percentage of quadrats sampled in which the species was present)
- Relative frequency (the percentage that the species value is of the total for all species, rather than in absolute form, i.e. relative to other species in the area)
- Abundance (the total number of individuals for each species per number of quadrats that it occupies)
- Relative abundance (relates the value for comparison with the other species)
- Density (relates total number of individuals of a species to the total area sampled)
- Relative density (for comparison with other species occuring in the area)
- Cover (the aerial cover of a species related to the area sampled)
- Relative cover (relates the value obtained for each species for comparison with other species)
- The overall importance value of a species (determined by summing the relative density, relative frequency and relative dominance).

3.3 Sampling Techniques - Fauna

A total of four trap arrays were constructed in the two sites (one inside and outside each of the two sinkholes) for herpetological and invertebrate sampling. Trap arrays were located approximately 100 m from the edge of the sinkholes, thus excluding potential edge effects. The traps consisted of an array of three 2 m long wooden drift fences and pitfall traps (sunken five litre buckets, level with the ground) at each end of the three drift fences and one at the centre of the array (Figure 6 and Figure 7). While herpetological studies do typically have considerably longer drift fences, the methods used in this study were approved by a herpetological expert. In addition, it would have been physically impossible to place a 30 m drift fence inside a sinkhole. Such drift fences could be placed outside the sinkholes but this would result in inconsistent trapping methods from different sites and inaccurate comparison.

Moist cotton wool balls were placed in each pitfall trap as well as sufficient water to cover the base of each bucket, to provide moisture for any amphibians caught. A 50 x 50 cm plywood board was placed on small rocks to cover each pitfall trap so as to reduce evaporation of moisture and provide shade for any animals caught. Traps were checked early morning and late afternoon. Photographs were taken for identification purposes and numbers of individuals were recorded.

Figure 6: Array trap outside Site 2 sinkhole

Figure 7: Array trap inside Site 2 sinkhole

Sherman live traps (26 x 9 x 9 cm) were set out for the capture, identification, measurement and release of small mammals. Two sets of traps were set up in paired 4 x 4 trap grids in each sinkhole (i.e. two sets inside and two sets outside) - totalling 128 traps. Each 4 x 4 trapping grid was placed 50 m apart, from the other set of trap grids. Given the limited space within the sinkholes, reaching the desired distances between grids and traps was not always possible, nevertheless traps were placed as far apart as possible (always greater than one metre). Traps were baited with a mixture of rolled oats, peanut butter, sunflower oil and salt, as well as dried sunflower seeds. Once placed in the grid, traps were covered with either 25 x 50 cm plywood boards or grass and rocks to provide protection from the elements for any animals caught (Figure 8 and Figure 9). Traps were checked early morning and late afternoon and rebaited every third day.

Figure 8: Sherman trap covered with plywood board

Figure 9: Sherman trap covered with plant material

Sweep netting using hand nets for sampling invertebrates was undertaken at all sites along random transects. Transects were conducted at random inside and outside the sinkholes. Inside transects were located throughout the sinkhole. Outside transects were located at various sites around the sinkhole, approximately 100 m away from the edge. Equal numbers of transects of equal length were conducted for both sites, both inside and outside the sinkholes. Active searching was also conducted during the day to find reclusive species, for equal lengths of time in each site. This involved looking under large rocks and within crevices etc. to locate scorpions, lizards and other sheltered species. Species that were easily visible (basking on rocks) were also recorded and identified. The presence of droppings and spoor were also noted and samples of droppings were collected for later identification.

Photographs were also taken of droppings and spoor for identification purposes. This was done at all sites. All species were identified in the field, where possible, and released immediately. Where identification in the field was not possible, photographs were taken of the specimens for later identification at the University of the Witwatersrand.

Invertebrate species were identified to at least Order level or as far as possible. Scorpions were identified using Leeming (2003), insects with Picker *et al. (*2004) and spiders using (Leroy and Leroy, 2003). Mammal species were identified using Walker (1996) and Apps

(2000). Reptiles were identified using Branch (1998) and amphibians using Carruthers (2001).

The trapping and marking procedures described here for all vertebrate fauna were approved by the Animal Ethics Committee of the University of the Witwatersrand (Ethics Clearance Number 2008/43/01).

3.4 Data Analysis

3.4.1 Environmental variables

To compare differences between cover values for all environmental variables, data were arcsine transformed, to correct for normality, and analysed using a factorial ANOVA in which the environmental variables (rocky cover, plant litter, grass, forbs, woody and bare ground) were the dependent variables and the sites (sinkhole one or sinkhole two) were the independent variables. Specific differences were tested using the Fishers Post-hoc test.

Environmental variables were then compared for differences between the location of the variables (inside or outside the sinkholes) using a Generalised Linear Model (GLM), where environmental variables were again the dependent variables and location independent. Specific differences were tested using the Fisher’s Post-hoc test.

The average cover for each environmental variable (rocky cover, plant litter, grass, forbs, woody and bare ground) was evaluated for any significant differences between the values obtained inside and outside the sinkholes using Chi-squared tests. Values obtained outside the sinkhole were said to be the observed values, while inside values were the expected values.

3.4.2 Floral Analysis

The cover for each individual plant species was arcsine transformed and analysed using a Generalised Linear Model (GLM) to determine significant differences between cover values recorded inside and outside the sinkholes. Growth type, leaf type and seed dispersal types were the dependent variables and location (inside or outside) were the independent variables. Specific differences were then further analysed using Fishers Post-hoc tests.

The cover for growth type, leaf type and seed dispersal type were each evaluated for any significant differences between the values obtained inside and outside the sinkholes using Chi-squared tests. Values obtained outside the sinkhole were said to be the observed values, while inside values were the expected values.

Diversity was measured for flora, using the Shannon-Weiner Diversity Index:

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

where H' is the index of species diversity given by summing the proportion of total sample belonging to the i^{th} species (p_i) multiplied by the natural log ($\ln p_i$). Richness (S) was the total number of species found either inside or outside the sinkholes. Evenness (J') was calculated, by dividing H' by the maximum possible diversity (ln of S), and compared for both inside and outside the sinkholes.

3.4.3 Multivariate Analysis

A multivariate analysis, using the CANOCO^{TM} program, was also conducted for the 40 quadrats sampled, to evaluate any relationships between the plant species and environmental variables. Multivariate analyses seek associations between variables so that plausible relationships can be identified, particularly when there may several independent and dependent variables (Lepš and Šmilauer, 2003). The analysis arranges species along gradients of change based on the species co-variation across all quadrats. These patterns are then associated with various environmental factors. Though the analysis does not have any statistical significance, it is useful in predicting and identifying plausible relationships that can be further studied and analysed.

Ordination arranges points, such that points that are close together correspond to sites that are similar in species composition and that points that are far apart correspond to sites that are dissimilar in species composition. We can use such an analysis to summarise community patterns and compare with our knowledge of environmental conditions (Lepš and Šmilauer, 2003). A principal components analysis (PCA) was performed, which searches for any environmental variable that best explains the species composition. The longer the vector, the greater the effect the variable has on species composition. A canonical correspondence analysis (CCA) was performed, where the plant species and all inside and outside quadrats were arranged according to their correspondence with the environmental variables (rocky cover, plant litter, grass, forbs, woody and bare ground). A CCA searches for the best explanatory variables within the data set.

Of the six environmental estimates measured, only three (plant litter, rock and bare ground cover) are plotted in the multivariate analysis. Grass, forb and woody cover would automatically form a correlation with specific species based on their growth type. These were thus excluded so as to more clearly examine any relationship between the other environmental variable.

3.4.4 Faunal Analysis

To compare differences in the number of individuals between outside values for all animals found, data were arcsine transformed and analysed using a GLM, in which the number of individuals per animal class (Amphibia, Arachnida, Insecta, Mammalia, Myriapoda and Reptilia) were the dependent variables and the location of the classes (inside or outside the sinkholes) were the independent variables. Specific differences were tested using the Fishers Post-hoc test.

Chi-squared tests were performed to determine any significant differences between the number of recorded occurrences outside and inside the sinkhole for each of the vertebrate (Amphibia, Mammalia and Reptilia) and invertebrate groups (Arachnida, Insecta and Myriapoda), where the number of recorded occurrences outside the sinkholes was the observed values and those recorded inside the sinkhole were the expected values.

The Shannon-Weiner Diversity Index, as discussed earlier for the floral analyses, was again used as a diversity measure for fauna.

4. RESULTS

4.1 Environmental Conditions

Based on initial visual observations, both sinkholes appeared to consist of considerably more woody species than the surrounding areas. There are considerably more trees located inside the sinkholes, with the deeper parts of the sinkholes being dominated entirely by woody species with little or no grass species. Grasses appeared to dominate the majority of slopes inside the sinkhole. Both sinkholes were very rocky with scattered stones throughout the sites.

No significant differences between environmental variables were found between site 1 and site 2 ($F_{6, 31} = 2.96$, $p < 0.01$). Following this, Site 1 and Site 2 were grouped together for further analyses.

Significant differences were found between outside values for the environmental variables ($F_{10, 226} = 14.46$, $p < 0.01$). Based on post-hoc results, outside the sinkholes, grass was found to have the highest cover values (37.56 %), which was significantly higher than all other environmental variables ($F_{10, 226} = 14.46$, $p < 0.01$) as seen in Figure 10. Forb cover was the next highest (27.82 %), followed by bare ground (25.35 %). No significant difference was found between forbs and bare ground cover, but they were significantly higher than plant litter, rock and woody cover ($F_{10, 226} = 14.46$, $p < 0.01$). No significant difference was found between plant litter (16.58 %) and rock cover (13.79 %) ($F_{10, 226} = 14.46$, $p < 0.01$). Woody cover (4.22 %) was significantly lower than all other environmental variables ($F_{10, 226} = 14.46$, $p < 0.01$).

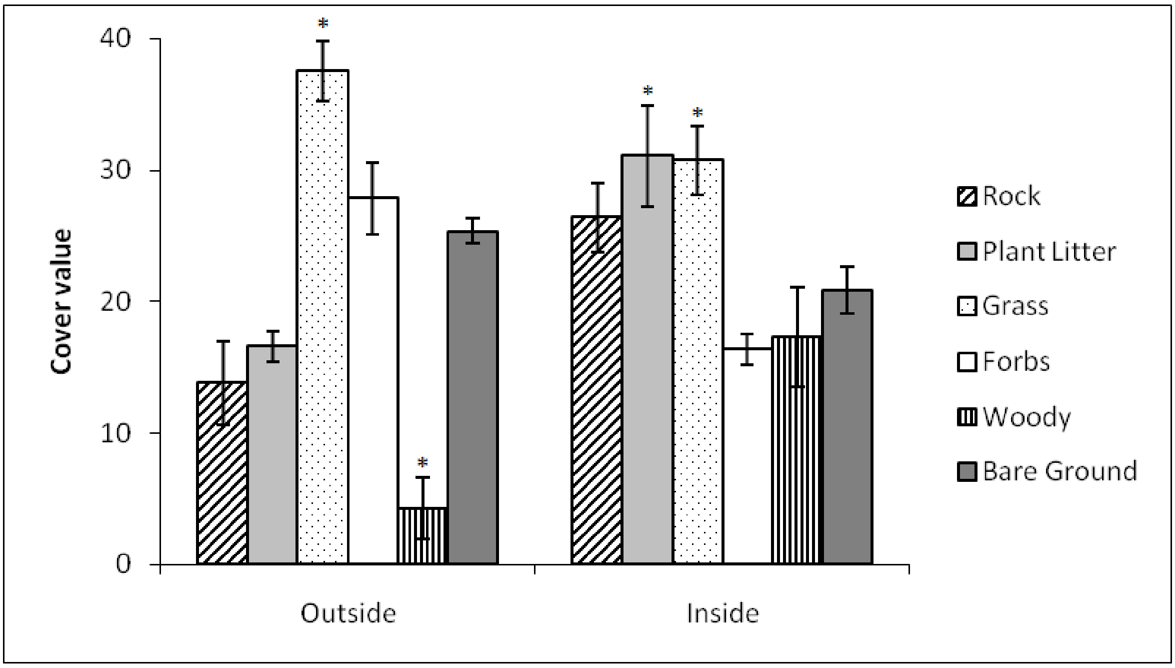

Figure 10: Graph showing the average values for each environmental variable as per location with standard error bars (* indicates significant difference as per Post-hoc test).

Significant differences were found between inside values for the environmental variables ($F_{10, 226} = 14.46$, $p > 0.05$). Post-hoc tests revealed that inside the sinkholes, plant litter (31.06 %), grass (30.75 %) and rock (26.39 %) cover were the environmental variables with the highest cover values, while bare ground (20.86 %), woody (17.27 %) and forb (16.38 %) cover were the lowest. No significant differences were found between the three highest variables (plant litter, grass and rock) ($F_{10, 226} = 14.46$, $p > 0.05$) or the three lowest (forbs, woody and bare ground) ($F_{10, 226} = 14.46$, $p > 0.05$). Plant litter and grass cover were found to be significantly higher than forb ($F_{10, 226} = 14.46$, $p < 0.001$), woody ($F_{10, 226} = 14.46$, $p < 0.001$) and bare ground cover ($F_{10, 226} = 14.46$, $p < 0.05$). Rock cover was significantly higher than forb ($F_{10, 226} = 14.46$, $p < 0.05$) and woody cover ($F_{10, 226} = 14.46$, $p < 0.05$) but not bare ground cover ($F_{10, 226} = 14.46$, $p > 0.05$).

Rock cover was found to be significantly lower outside the sinkholes in comparison to inside values, ($\chi^2_1 = 6.01$, $p = 0.05$). Plant litter was significantly lower outside the sinkholes ($\chi^2_1 = 6.75$, $p = 0.01$). The difference between grass cover was not significantly different, but was higher outside the sinkholes ($\chi^2_1 = 1.51$, $p > 0.05$). The average forbs cover was higher outside the sinkholes ($\chi^2_1 = 7.99$, $p = 0.01$). Woody cover was significantly lower outside the sinkholes ($\chi^2{}_1 = 9.86$, $p = 0.01$). Bare ground cover was higher outside the sinkholes, but not significantly so ($\chi^2{}_1 = 0.96$, $p > 0.05$).

4.2 Flora

The species richness curve (Figure 11) obtained shows an eventual levelling off as the quadrat size increases, indicating that a near maximum number of species had been recorded after the 8 x 8 m quadrat had been thoroughly sampled. A total of 17 species were identified in the 1 m^2 quadrat. The 2 x 2 m quadrat revealed 29 species, an increase of 12 new species. In the 4 x 4 m quadrat 38 species were recorded, a further increase of nine species. Only six additional plants were found in the 8 x 8 m quadrat (44 species in total). While such curves illustrate the rate at which new species are found, they do not directly reveal total species richness. More effort would reveal more species (Magurran, 2004). However, the increased amount of effort that would have been required to find further species would not have been justified had a larger area been searched. It was thus decided that in further sites examined in this study, an 8 x 8 m quadrat would be sufficient to adequately sample the plant species in a given area.

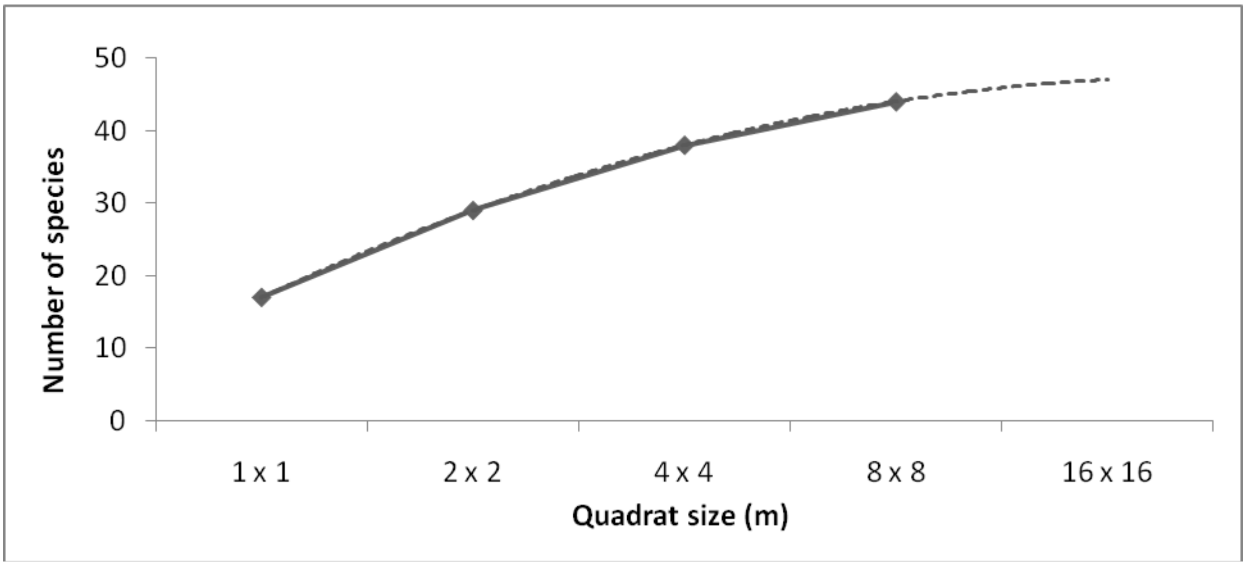

Figure 11: Increasing effect of size of quadrat on the number of species recorded

A total of 77 plant species were found throughout the sites. Of these, 28 species (36.4 %) were recorded as occurring both inside and outside the sinkhole, while 28 species (36.4 %) were found only outside the sinkholes. Species occurring exclusively inside the sinkhole were slightly fewer, with 21 species (27.3 %) occurring only inside the sinkholes.

4.2.1 Growth type

As seen in Figure 12, grass was the most abundant growth type found outside the sinkholes with an average percentage cover of 10.79 %, followed by herbaceous (7.92 %), woody (6.57 %) and succulent cover (5.19 %). The only significant difference was found between grass and woody cover ($F_{6, 146} = 2.20$, $p < 0.05$).

Inside the sinkholes, grass was again the most abundant growth type (8.19 %) but this was only marginally higher than succulent and woody cover (7.97 % and 7.95 % respectively). The herbaceous growth type yielded the lowest average percentage cover inside the sinkholes (5.19 %). Herbaceous cover was found to be significantly lower than woody cover inside the sinkholes ($F_{6, 146} = 2.20$, $p < 0.05$).

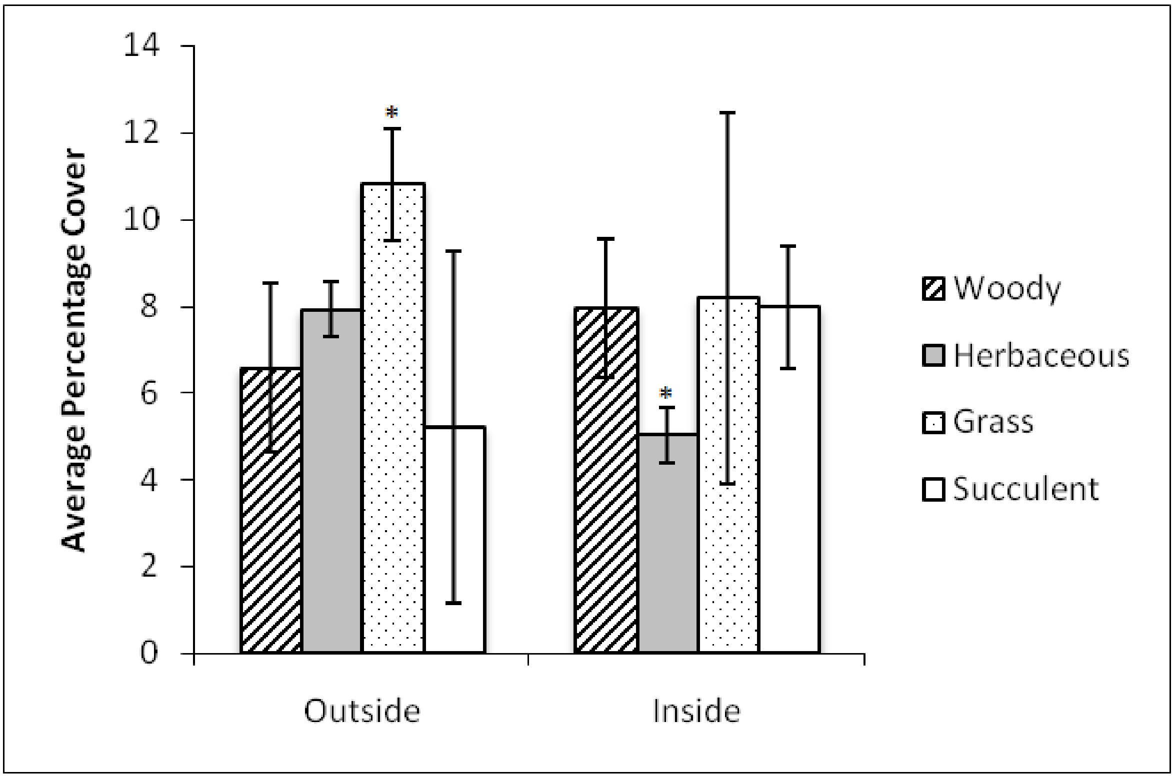

Figure 12: Average percentage cover obtained for each growth type, inside and outside of the sinkholes with standard error bars (* indicates significant difference).

Herbaceous cover was found to be significantly higher outside the sinkholes in comparison to values obtained inside the sinkholes ($\chi^2{}_1 = 78.31$, $p = 0.01$). Grass cover was also significantly higher outside the sinkholes ($\chi^2{}_1 = 5.74$, $p = 0.05$). Woody ($\chi^2{}_1 = 5.04$, $p = 0.05$) and succulent ($\chi^2{}_1 = 3.88$, $p = 0.05$) cover were significantly higher inside the sinkholes

4.2.2 Leaf type

As seen in Figure 13, the average percentage cover, outside the sinkholes, of broad-leaved plants (3.52 %) was significantly lower in comparison with fine-leaved plants (7.78 %) ($F_{2, 75} = 2.44$ $p < 0.05$). The percentage cover of broad (5.56 %) versus fine-leaved (5.26 %) plants was not significantly different inside the sinkholes ($F_{2, 75} = 2.44$ $p < 0.1$).

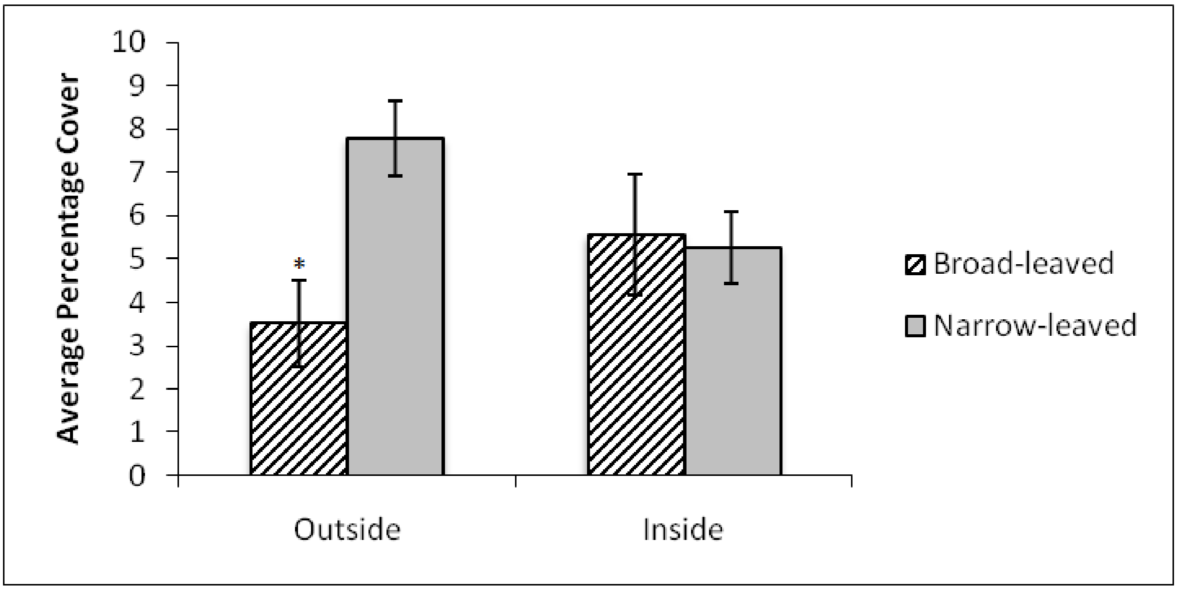

Figure 13: The average percentage cover obtained for the different leaf types inside and outside the sinkholes, with standard error bars (* indicates significant difference).

The cover of broad-leaved plants outside the sinkholes was significantly lower in comparison to broad-leaved plant cover inside the sinkholes ($\chi^2_1 = 8.87$, $p = 0.01$). Fine-leaved plant cover was significantly higher outside the sinkholes ($\chi^2_1 = 63.95$, $p = 0.01$).

4.2.3 Seed dispersal type

As seen in Figure 14, outside the sinkholes, the percentage cover of plants with wind dispersal (7.09 %) was only slightly higher than those with animal (6.58 %) or other (7.06 %) types, but not significantly so ($F_{4, 148} = 1.18$, $p < 0.05$). Inside the sinkholes, the average percentage cover of plants with other (9.41 %) types of seed dispersal was significantly higher than the animal dispersed seed types (4.56 %), but not with wind dispersed seeds (5.56 %) ($F_{4, 148} = 1.18$, $p < 0.05$).

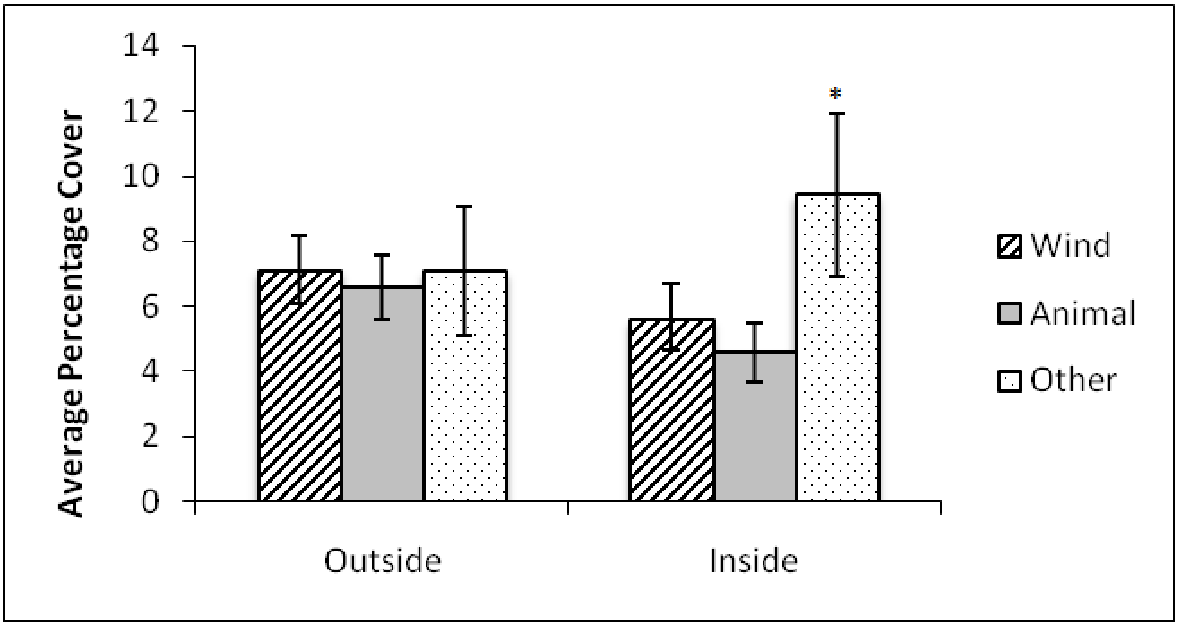

Figure 14: The average percentage cover obtained for each of the seed dispersal types inside and outside the sinkholes, with standard error bars (* indicates significant difference).

Wind dispersed (χ^2_{1} = 10.41, p = 0.01) and animal dispersed (χ^2_{1} = 36.84, p = 0.01) seeds were significantly higher outside the sinkholes. In contrast, other dispersed seeds were significantly lower outside the sinkholes (χ^2_{1} = 6.47, p = 0.05).

4.2.4 Floral composition

As seen in Table 1, *Tagetes minuta* (Khaki weed) is the most frequently occurring species overall (outside and inside quadrats combined) and for the inside quadrats. *Chaetacanthus glandulosa* was the most frequently occurring species outside the sinkhole. *Digitaria longiflora* was the second most frequent species for combined and featured as one of the most frequent species in both inside and outside the sinkholes.

Table 1: Floral composition for the highest scoring species per location and overall effect

Floral composition		**Combined**	**Outside**	**Inside**
Frequency	1	*Tagetes minuta*	*Chaetacantus glandulosa*	*Tagetes minuta*
	2	*Digitaria longiflora*	*Nidorella anomala*	*Dichondra micrantha*
	3	*Chaetacanthus glandulosa*	*Digitaria longiflora* *Elionurus muticus* *Setaria sphacelata* *Senecio lydenburgensis*	*Asparagus setaceus* *Digitaria longiflora* *Melinus nerviglumis*
Abundance	1	*Tagetes minuta*	*Euryops transvaalensis*	*Tagetes minuta*
	2	*Eurypos transvaalensis*	*Ophioglossum polyphyllum*	*Celtis africana*
	3	*Celtis Africana*	*Ziziphus zeyheriana*	*Oxalis obliquifolia*
Density	1	*Tagetes minuta*	*Digitaria longiflora*	*Tagetes minuta*
	2	*Digitaria longiflora*	*Euryops transvaalensis*	*Dichondra micrantha*
	3	*Celtis Africana*	*Chaetacantus glandulosa*	*Celtis africana*
Cover	1	*Digitaria longiflora*	*Digitaria longiflora*	*Tagetes minuta*
	2	*Setaria sphacelata*	*Elionurus muticus*	*Melinus nerviglumis*
	3	*Elionurus muticus*	*Setaria sphacelata*	*Grewia flava*
Importance Value	1	*Tagetes minuta*	*Digitaria longiflora*	*Tagetes minuta*
	2	*Digitaria longiflora*	*Elionurus muticus*	*Dichondra micrantha*
	3	*Setaria sphacelata*	*Chaetacantus glandulosa*	*Melinus nerviglumis*

The most abundant species occurring overall was Khaki weed, which was also the most abundantly occurring species for the quadrats located inside the sinkholes. The most abundant species for the outside quadrats was *Euryops transvaalensis,* which was second most abundant overall. The third most abundant species overall was *Celtis Africana* (White Stinkwood), which was also the second most abundant species inside the sinkholes.

Khaki weed was by far the most dense species overall and inside the sinkholes. *Digitaria longiflora* was the most densely occuring species outside the sinkhole, followed by *Euryops transvaalensis* and *Chaetacanthus glandulosa*. Neither of these species contributed to the overall density, which was made up of *Digitaria longiflora* and White Stinkwood. White Stinkwood was second densest plant inside the sinkholes.

Digitaria longiflora, Setaria sphacelata (Small creeping foxtail) and *Elionurus muticus* (Sour grass) were the three species with the highest relative cover values overall and for quadrats occurring only outside the sinkhole. Inside quadrats differed substantially with Khaki weed*, Melinus nerviglumis* (Bristle leaf red top) and *Grewia flava* (Raisin bush) exhibiting the highest relative cover scores.

Khaki weed featured as the most important species for the overall effect as well as inside the sinkholes. *Digitaria longiflora* was the most important species outside the sinkhole and second highest for the overall quadrats. Small creeping foxtail was third most important overall, despite not featuring in either of the inside or outside quadrats. The overall importance values exhibited similarities to quadrats located both inside and outside the sinkholes. A complete list of all information for all recorded species is given in Appendix A. A total of 77 plant species were recorded, of these 28 plant species were found both inside and outside the sinkholes. 28 species were recorded only outside the sinkholes, whereas 21 plant species were found exclusively inside the sinkholes.

4.2.5 Shannon-Weiner Diversity Index

The Shannon-Weiner Diversity Index (H') was higher for plant species outside the sinkhole, suggesting that the numbers of individuals are more evenly distributed between species, than for species inside the sinkhole (Table 2). The total number of species (S) found inside and outside the sinkholes is relatively similar. Evenness (J') is again higher outside the sinkhole, than for species inside the sinkhole. This suggests that species are not evenly distributed inside the sinkhole and the community may be dominated by one or more species. This is likely to be Khaki weed, as it featured prominently in the floral composition analyses.

Table 2: Results obtained for the Flora Shannon-Weiner Diversity Index

	Outside	Inside
H'	-3.51	-1.25
S	56	49
J'	-0.87	-0.32

4.2.6 Multivariate Analysis

From Figure 15, we can see that the plant litter and bare ground environmental varibales have the longest vectors and therefore may influence the type of species found in each quadrat. The influence of rock is considerably lower than the other environmental variables. The plant litter vector is located opposite to bareground, suggesting that they are inversely proportional, i.e. in quadrats where plant litter is high, bare ground would be low and vice versa. Rock cover lies between the other vectors suggesting no particular association with other environmental variables.

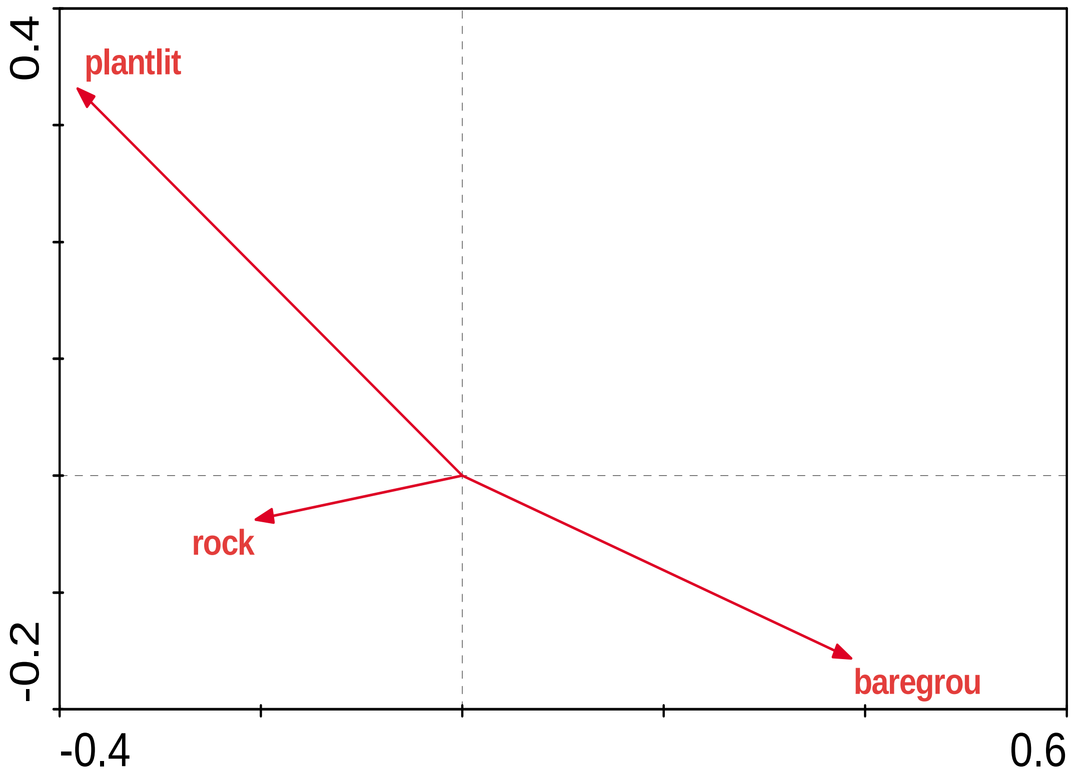

Figure 15: Principal components analysis (PCA) of environmental variables

The CCA shows a broad spread of species distribution (Figure 16). The majority of species do not correlate to a specific environmental variable, but rather lie between vectors. This suggests that no particular environmental variable influences the type of species that will establish in an area. Only two species are closely associated with the plant litter environmental variable and these are woody species, as would be expected, as these species contribute to plant litter. Few species show particular preference for individual environmental vectors, suggesting that a combination of factors may affect their occurrence. *Melinis nerviglumis* and *Commelina erecta* are closely aligned on the rock environmental variable, suggesting that they are regularly found in rocky areas. The majority of species lie between bare ground and plant litter. This suggests that other environmental variables, not included in this study, may contribute to the occurrence of individual species.

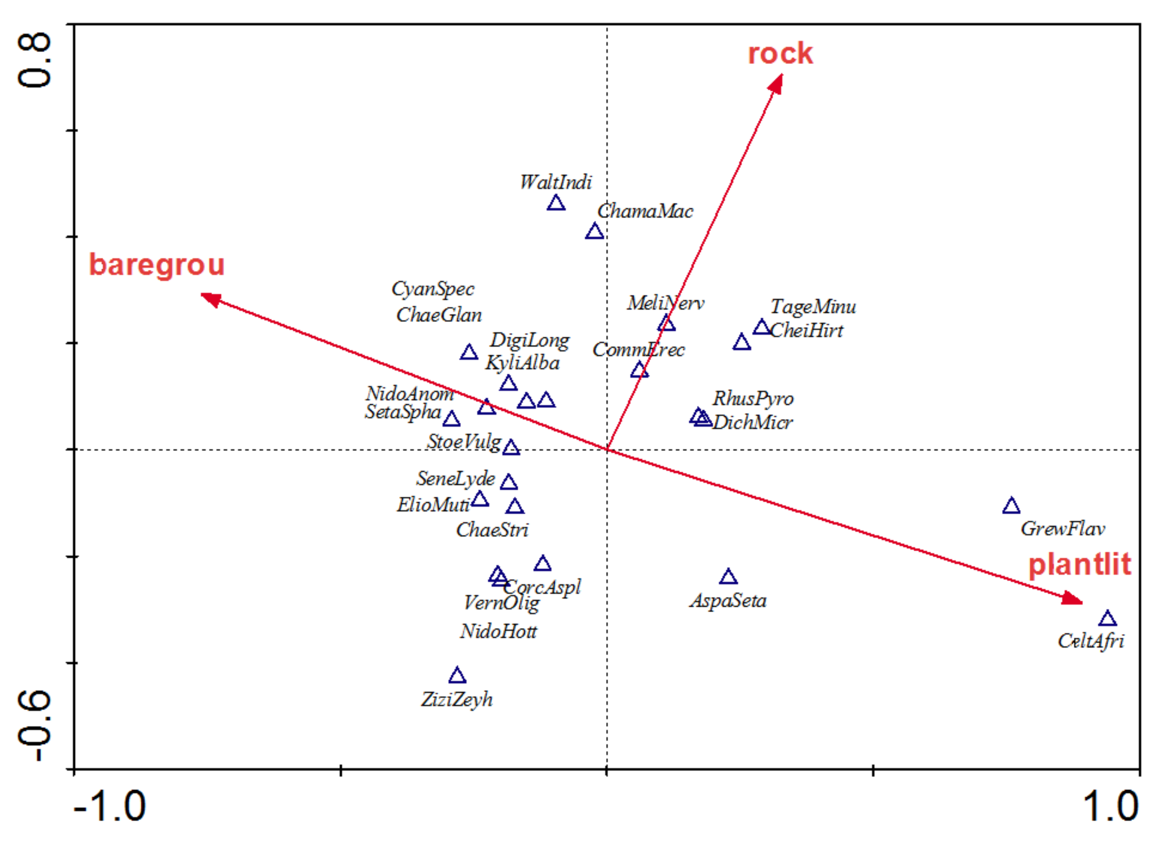

Figure 16: Multivariate analysis (CCA) showing the relationships between plant species (species with highest importance value are shown) and environmental variables (red arrows).

As seen in Figure 17, there is a certain degree of separation between inside and outside quadrats, as related to environmental variables. Outside quadrats show a tendency to associate predominantly with bare ground, with only a few quadrats tending towards the rock environmental variable. In contrast, inside quadrats show a tendency to associate with the plant litter and rock environmental variables, while very few inside quadrats show a tendency towards the bare ground environmental variable. Only one inside quadrat could be considered an outlier (21), as it is located some distance from the closest environmental variable (rock).

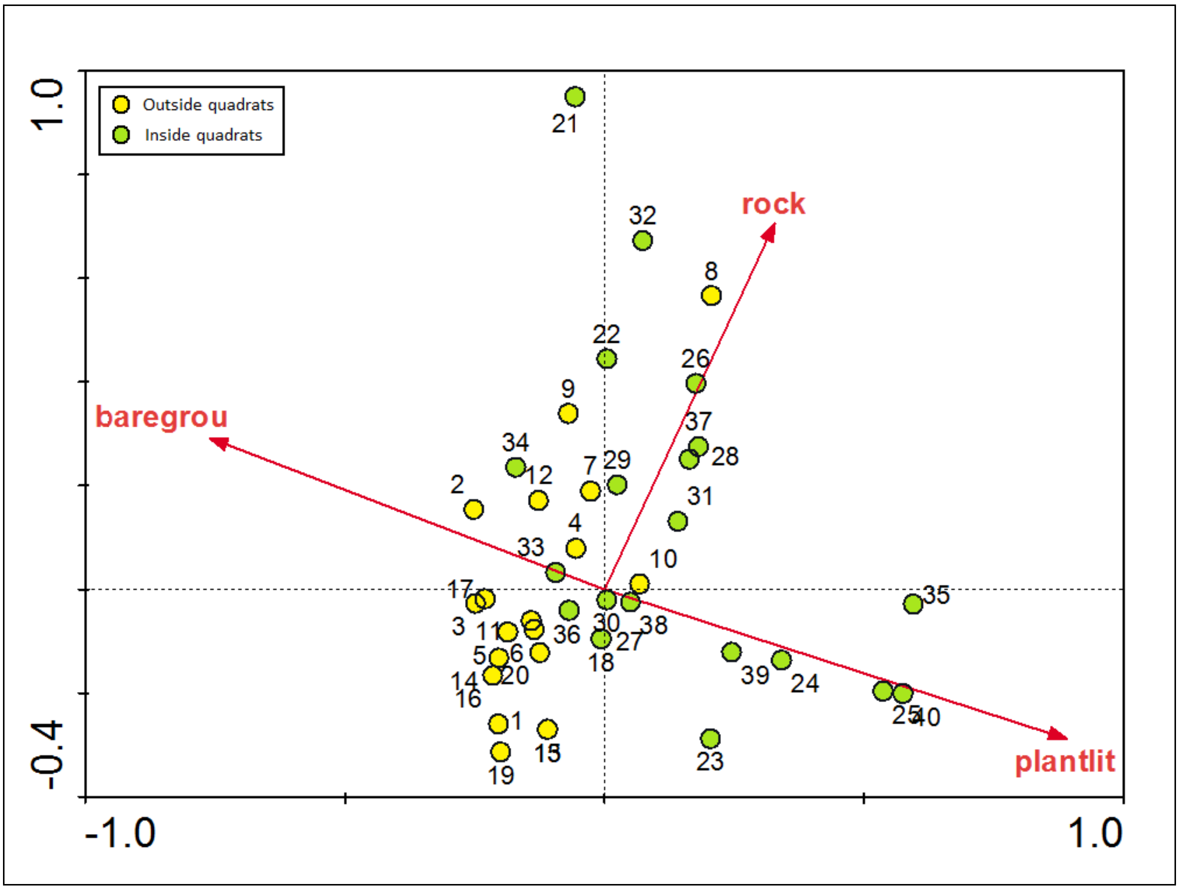

Figure 17: Multivariate analysis (CCA) showing the relationships between quadrats and environmental variables

In Figure 18, the relationships between environmental variables, quadrats and species are again plotted using a CCA. It is clear that some species show a tendency to clump with certain quadrats, further highlighted in Figure 19, which shows only the quadrats and species. *Celtis africana, Grewia flava, Asparagus setaceus* and *Tagetes minuta* show clear correspondence with inside quadrats, indicating that they may be expected to occur exclusively inside the sinkholes. Confirming this, *C. africana* and *G. flava* were recorded only inside the sinkholes, while *A. setaceus* and *T. minuta* were found predominantly inside the sinkholes (90 % and 99 % respectively). Refer to Appendix A for a complete list of all species found inside and outside the sinkholes.

A number of species also show a clear affinity towards the outside quadrats, indicating that they are more abundant outside the sinkholes. This suggests that conditions outside the sinkhole may be more suited to their optimal growth requirements.

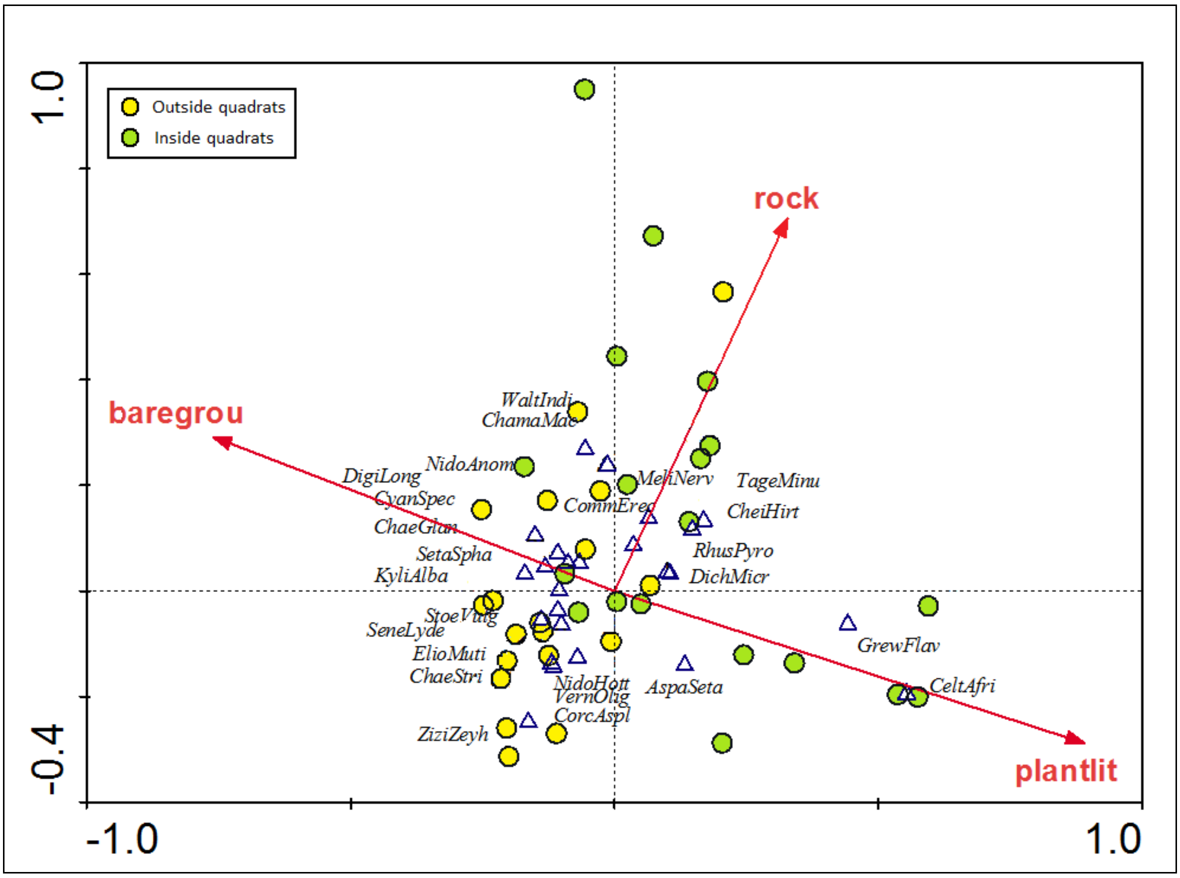

Figure 18: Multivariate analysis (CCA) showing relationships between quadrats, environmental variables and species.

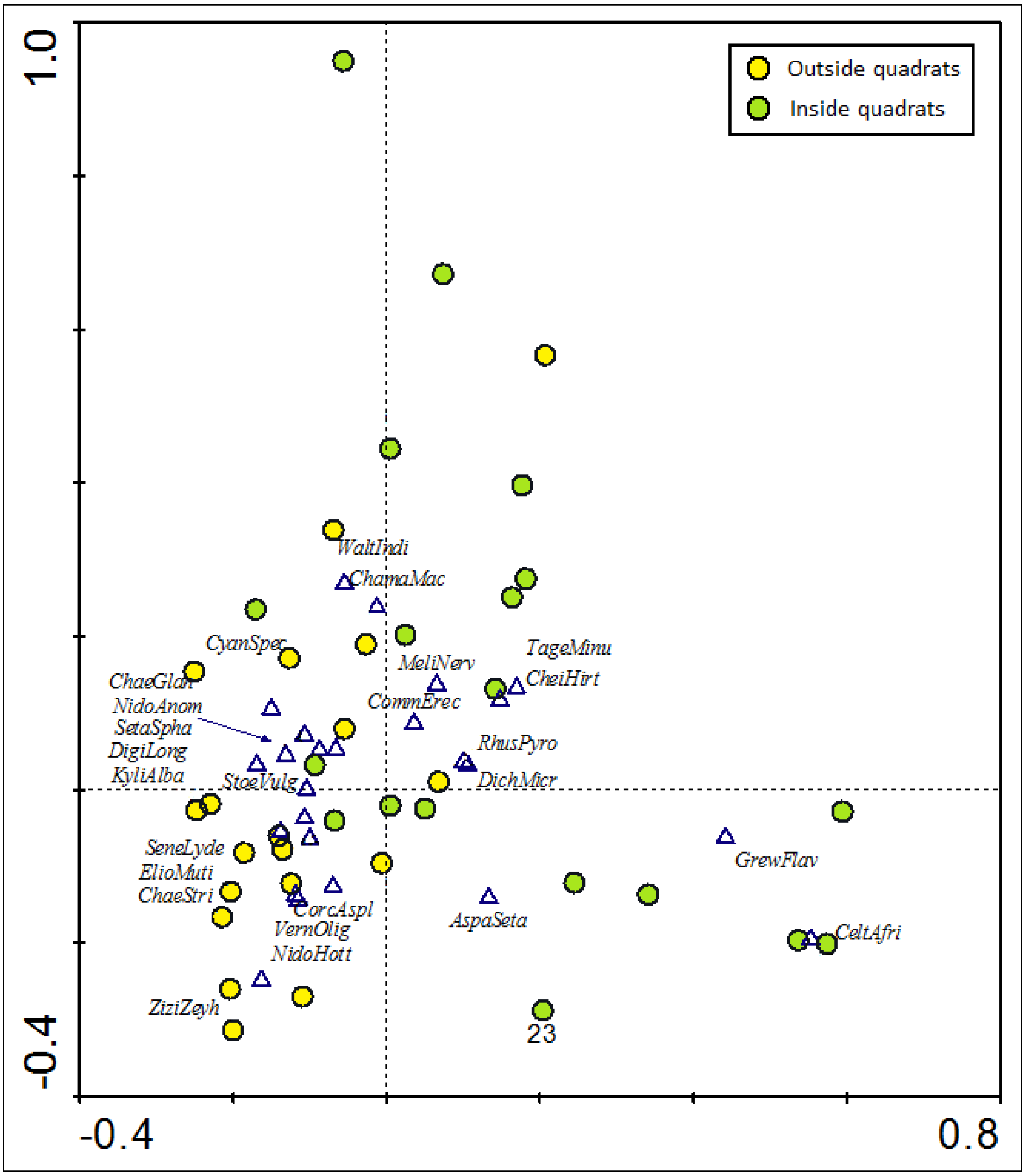

Figure 19: Multivariate analysis (CCA) showing relationships between quadrats and species.

4.3 Fauna

A total of six animal classes were recorded in the study sites. These were Amphibia, Arachnida, Insecta, Mammalia, Myriapoda and Reptilia. Animal classes showed similar abundance patterns for inside and outside the sinkholes, as seen in Figure 20.

Significant differences were found between animal classes both outside and inside the sinkholes ($F_{10, 226} = 8.73$, $p < 0.01$). Outside the sinkholes, Insecta (50.90 %) were the most abundant, followed by Arachnida (25.57 %), Myriapoda (13.80 %), Mammalia (5.66 %), Reptilia (2.71 %) and Amphibia (1.36 %). Insecta was significantly higher than Arachnida and Myriapoda ($F_{10, 226} = 8.73$, $p < 0.01$). Amphibia was significantly lower than all other animal classes ($F_{10, 226} = 8.73$, $p < 0.01$).

Inside the sinkholes, Insecta (63.71 %) were again most abundant, followed by Arachnida (20.86 %), Myriapoda (8.57 %), Amphibia (4.00 %), Mammalia (1.71 %) and Reptilia (1.14 %). The presence of Insecta and Arachnida were significantly higher than that of Mammalia and Reptilia ($F_{10, 226} = 8.73$, $p < 0.01$). No other significant differences were recorded between animal classes inside the sinkholes ($F_{10, 226} = 8.73$, $p < 0.01$).

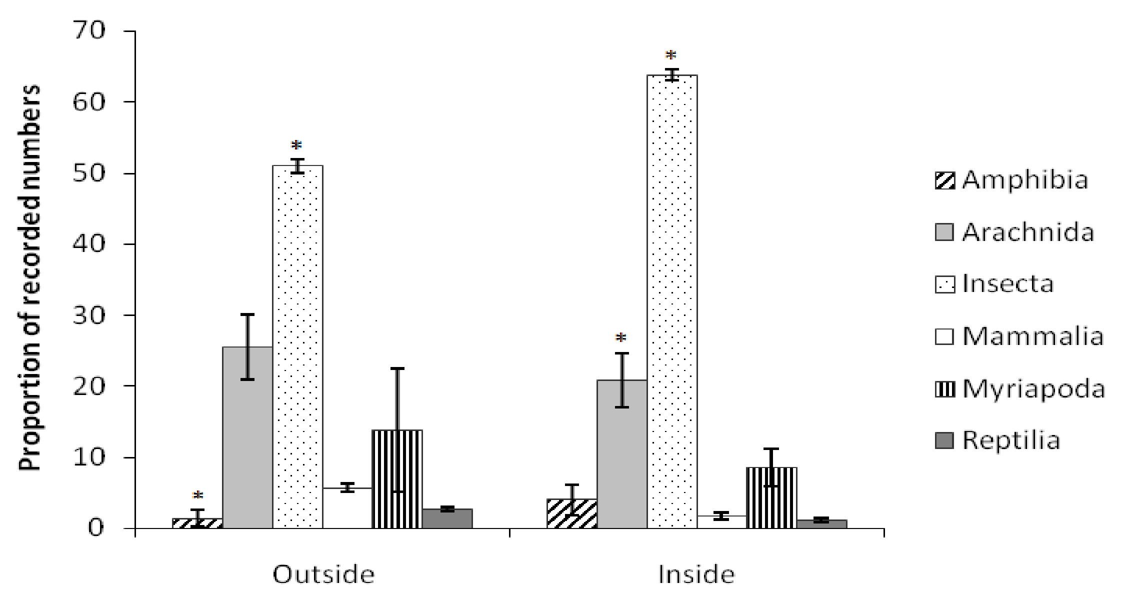

Figure 20: The proportion of recorded numbers of each animal class found per location (* indicates significant difference).

4.3.1 Vertebrates

A total of three vertebrate classes were found during the trapping session. These were Amphibia, Mammalia and Reptilia. The proportion of species found per class, for inside and outside the sinkholes, is displayed in Figure 21. Amphibians were found in significantly higher numbers inside the sinkholes ($\chi^2{}_1 = 27.47$, $p = 0.01$). In contrast, the presence of mammals ($\chi^2{}_1 = 17.31$, $p = 0.01$) and reptiles ($\chi^2{}_1 = 15.38$, $p = 0.01$) was significantly higher outside the sinkholes. The results per class are discussed in further detail below.

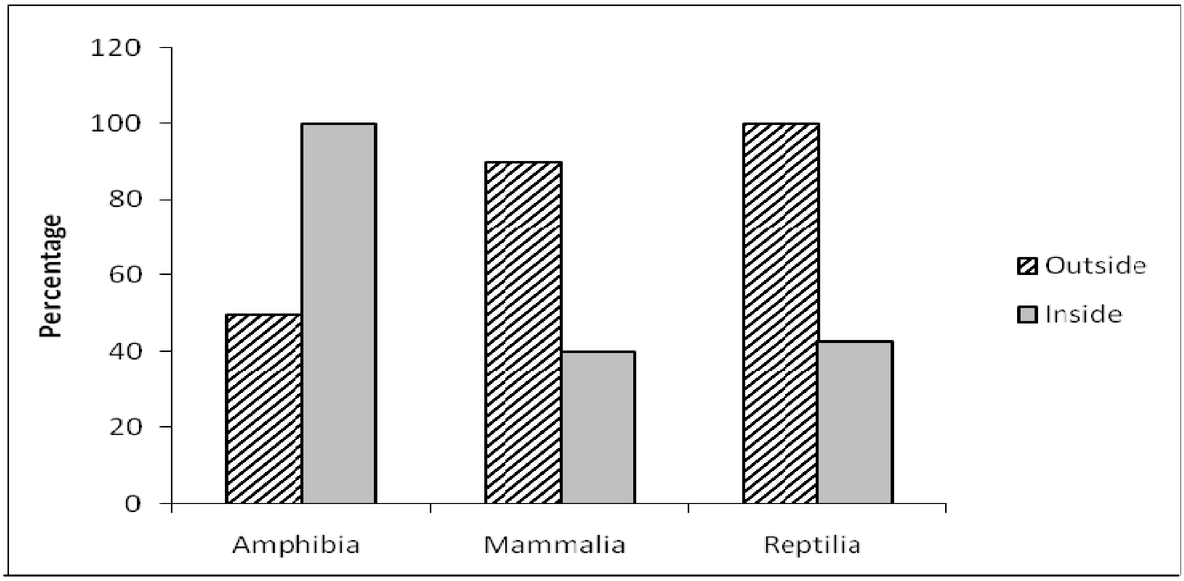

Figure 21: Proportion of recorded vertebrate species per location

Mammals

A total of nine mammal species were recorded in the study areas, either by direct observation or indirectly through identification of tracks or droppings. Of these, eight species (88 %) were found to occur outside the sinkhole, while three species (33 %) were found inside the sinkhole (Table 3). Of the three species found inside the sinkhole, only one species (11 %) was recorded exclusively inside the sinkhole. This was the only rodent caught in the Sherman Live traps, which escaped before positive identification was possible. It is most likely to have been either *Mastomys natalensis* or *Saccostomus campestris*, however this cannot be confirmed.

A total of two species (22 %) were recorded as occurring both inside and outside the sinkholes. These were *Hystrix africaeaustralis* (porcupine*)* and *Pelea capreolus* (Grey Rhebok*).* Only indirect evidence of the porcupine was found (spoor, droppings and quills), whereas the grey rhebok was observed on site.

Of the eight mammal species occurring outside the sinkhole, six (67 %) of these were recorded as occurring exclusively outside the sinkhole. These were *Xerus inauris* (Ground Squirrel), *Canis mesomelas* (Black Backed Jackal), *Lepus saxatilis* (Scrub Hare), *Raphicerus campestris* (Steenbok), *Sylvicapra grimmia* (Common Duiker) and *Cynictis penicillata* (Yellow Mongoose). The total number of recorded mammals occurring outside the sinkhole was 21, in comparison to only 8 inside the sinkhole.

Table 3: Mammal species observed according to location

Scientific name	**Common name**	**Outside**	**Inside**
Canis mesomelas	Black-backed jackal	✓	✗
Cynictis penicillata	Yellow mongoose	✓	✗
Hystrix africaeaustralis	Porcupine	✓	✓
Lepus saxatilis	Scrub hare	✓	✗
Pelea capreolus	Grey rhebok	✓	✓
Raphicerus campestris	Steenbok	✓	✗
Rodent sp.	-	✗	✓
Sylvicapra grimmia	Common duiker	✓	✗
Xerus inauris	Ground squirrel	✓	✗

Reptiles

A total of seven reptilian species were recorded in the study area, through direct observation or dropping identification (Table 4). Recorded occurrences of reptiles were again more abundant outside the sinkhole, with a total number of 12 reptile occurrences, in comparison to only four observed inside the sinkhole. All seven species were observed outside the sinkhole, while only three (42.9 %) of these species were recorded inside the sinkhole. These were *Pachydactylus affinis* (Transvaal Thick-toed Gecko), *Gerrhosaurus* *flavigularis* (Yellow-throated Plated Lizard) and *Panaspis walbergii* (Wahlberg's Snake-eyed Skink). No species were found to occur exclusively inside the sinkhole.

Table 4: Reptile species observed according to location

Scientific name	Common name	Outside	Inside
Cordylus vittifer	Transvaal Girdled Lizard	✓	✗
Gerrhosaurus flavigularis	Yellow-throated Plated Lizard	✓	✓
Pachydactylus affinis	Transvaal Thick-toed Gecko	✓	✓
Panaspis walbergii	Wahlberg's Snake-eyed Skink	✓	✓
Squamata sp. 1	-	✓	✗
Squamata sp. 2	-	✓	✗
Trachylepis capensis	Cape Thick-toed Gecko	✓	✗

Amphibians

A total of four amphibian species were recorded, these were identified as *Afrana angolensis* (Common River Frog), *Bufo gutturalis* (Guttural Toad), *Kassina senegalensis* (Bubbling Kassina) and *Schismaderma carens* (Red Toad). In contrast to mammals and reptiles, amphibians were more abundant inside the sinkholes with a total number of six recorded occurrences outside the sinkholes, in comparison with 14 occurrences inside.

Of the four amphibian species recorded, all four species (100 %) occurred inside the sinkhole (Table 5). Of these, only the Guttural Toad and the Bubbling Kassina were recorded outside the sinkhole (50 %). The Common River Frog and Red Toad were found to occur exclusively inside the sinkhole, with no recorded occurrences outside the sinkhole.

Table 5: Amphibian species observed according to location

Scientific name	Common name	Outside	Inside
Afrana angolensis	Common River Frog	✗	✓
Bufo gutturalis	Guttural Toad	✓	✓
Kassina senegalensis	Bubbling Kassina	✓	✓
Schismaderma carens	Red Toad	✗	✓

A total of 17 vertebrate species were recorded outside the sinkholes, consisting of 39 separate records. In comparison, only ten vertebrate species were recorded inside the sinkholes, made up of 26 observations.

4.3.2 Invertebrates

A total of three invertebrate groups (Arachnida, Myriapoda and Insecta) were found during the trapping session. The percentage of species found per class, for inside and outside the sinkholes, is displayed in Figure 22.

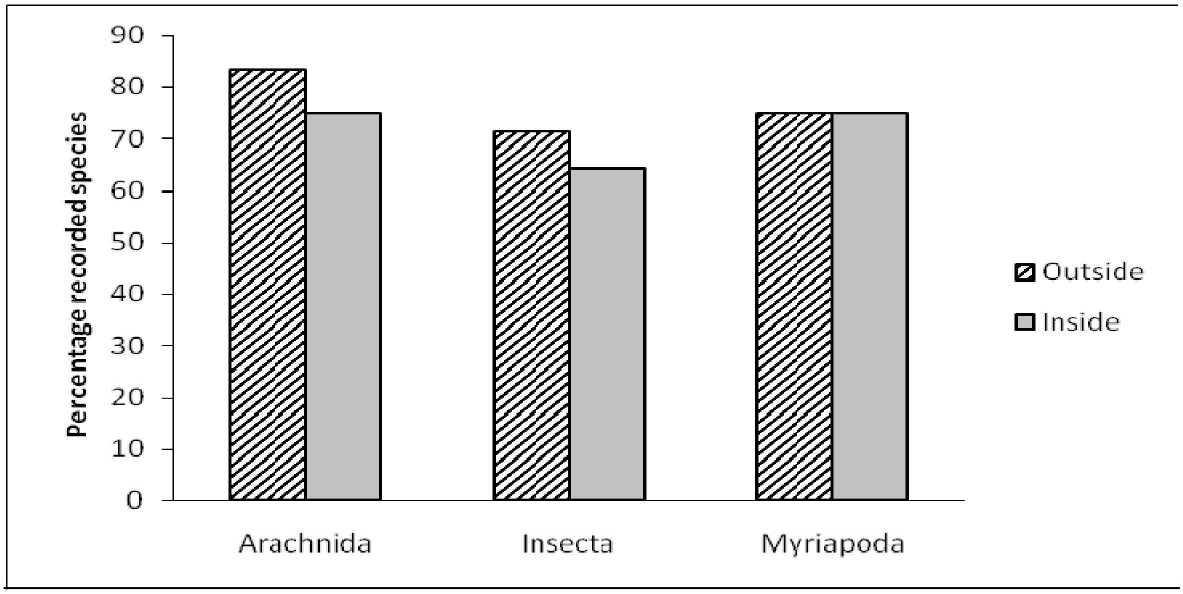

Figure 22: Percentage recorded invertebrate species per location

Arachnida occurred in significantly higher numbers outside the sinkholes, compared to numbers recorded inside the sinkholes ($\chi^2_{(1)} = 21.92$, $p = 0.01$). No significant difference was found between the total number of Insecta found outside and inside the sinkholes ($\chi^2_{(1)} = 0.004$, $p = 0.01$). Myriapoda yielded significantly higher numbers outside the sinkholes ($\chi^2_{(1)} = 8.91$, $p = 0.01$).

Arachnida

A total of 12 Arachnida species were recorded overall. Of these, two scorpion species (*Opistophthalmus glabrifrons* and *Uroplectes triangulifer*), one solifugae species and one mite species were found. The majority of species were recorded both outside and inside the sinkholes (Table 6). Ten Arachnida species were found outside the sinkhole and nine species were recorded inside the sinkholes. Three species were found to occur exclusively outside the sinkhole, while two species were found only inside the sinkhole. However, in each of these, only one record was found, so it is possible that more individuals may be found inside the sinkholes in further studies.

Table 6: Arachnid species observed according to location

Class	Scientific name	Outside	Inside
Arachnida	*Acari sp.*	✓	✓
Arachnida	*Araneae 1*	✓	✓
Arachnida	*Araneae 2*	✓	✗
Arachnida	*Lycosidae family 1*	✗	✓
Arachnida	*Lycosidae family 2*	✓	✓
Arachnida	*Lycosidae family 3*	✓	✗
Arachnida	*Neoscona blondeli*	✗	✓
Arachnida	*Opistophthalmus glabrifrons*	✓	✓
Arachnida	*Solifugae sp.*	✓	✓
Arachnida	*Uroplectes triangulifer*	✓	✓
Arachnida	*Zodariidae family 1*	✓	✗
Arachnida	*Zodariidae family 2*	✓	✓

Insecta

A total of eight separate insect orders were identified from the 83 species collected over the trapping period (Table 7). Blattodea was the only order to be found exclusively inside the sinkholes, but not in significantly higher numbers ($\chi^2_{(1)} = 3.00$, $p > 0.01$). Coleoptera species were found both inside and outside the sinkholes, at significantly higher levels outside the sinkholes ($\chi^2_{(1)} = 5.21$, $p = 0.05$). Of the Hemiptera species, higher numbers were recorded outside the sinkholes but not at significantly higher numbers ($\chi^2_{(1)} = 0.94$, $p > 0.01$). Hymenoptera species were recorded at significantly higher numbers inside the sinkholes when compared to those occurring outside the sinkholes ($\chi^2_{(1)} = 4.17$, $p = 0.05$). Six species of Lepidopetera were recorded, three of which were Lepidoptera larvae. The three species of adult Lepidoptera (butterflies) were recorded only outside the sinkhole, whereas larvae were found both inside and outside the sinkholes. No significant differences between numbers outside and inside the sinkholes were recorded ($\chi^2_{(1)} = 3.77$, $p > 0.01$). Eight orthoptera species were found, with significantly higher numbers found inside the sinkholes ($\chi^2_{(1)} = 4.35$, $p = 0.05$). Phasmatodea were recorded in equal numbers outside and inside the sinkholes. A complete list of insect species recorded during the study is given in Appendix B.

Table 7: Insect orders observed according to location

Class	Order	Outside	Inside
Insecta	Blattodea	✗	✓
Insecta	Coleoptera	✓	✓
Insecta	Hemiptera	✓	✓
Insecta	Hymenoptera	✓	✓
Insecta	Lepidoptera	✓	✓
Insecta	Mantodea	✓	✓
Insecta	Orthoptera	✓	✓
Insecta	Phasmatodea	✓	✓

Myriapoda

A total of four Myriapoda species were observed on site (Table 8). Two species were observed both inside and outside the sinkholes, while one species each occurred only inside and outside the sinkholes respectively.

Table 8: Myriapoda observed according to location

Class	Scientific name	Outside	Inside
Myriapoda	*Chilopoda 1*	✓	✓
Myriapoda	*Diplopoda 1*	✓	✓
Myriapoda	*Diplopoda 2*	✓	✗
Myriapoda	*Diplopoda 3*	✗	✓

Species richness was slightly higher outside the sinkholes, with 73 different species found, compared to 66 species found inside. The total number of insect occurrences was relatively similar, with 373 recorded outside and 318 recorded inside the sinkholes.

4.3.3 Shannon-Weiner Diversity Index

The H’ values obtained for animal species outside and inside the sinkholes are similarly high (Table 9). This implies that individuals are evenly distributed between species, with no particular species being more dominant. The total number of species recorded outside the sinkholes is higher than those found inside the sinkholes. Additionally, the J’ values are similarly high, suggesting that species are evenly distributed both inside and outside the sinkhole.

Table 9: Results obtained for the Fauna Shannon-Weiner Diversity Index

	Outside	Inside
H’	-3.52	-3.47
S	90	76
J’	-0.78	-0.80

5. DISCUSSION

5.1 Environmental conditions

Distinct differences were recorded in the percentage cover of each environmental variable. It is expected that grassy species would tend to dominate outside the sinkhole, as well as inside the sinkholes, as the study area is located in the Grassland Biome, which is dominated by the Poaceae or Grass family (Rutherford and Westfall, 1994) and are naturally adapted for the environmental conditions. Although some woody species do occur, grasslands are maintained by biotic factors, such as persistent wood removal and indiscriminate use of fire over the centuries (Rutherford and Westfall, 1994), which would reduce the occurrence of woody species.

Where trees occur in the Grassland Biome, they are usually associated with local specialised niches, such as in the Bankenveld and higher altitude areas east of the escarpment (Rutherford and Westfall, 1994). Several species considered typical to Bankenveld were found in the study sites, including *Cheilanthes hirta, Celtis africana, Vernonia oligacephala, Rhus pyroides* and *Rhus rigida.* Of these *C. hirta, C. africana* and *R. rigida* were found exclusively inside the sinkholes, while, *V. oligacephala* was found only outside the sinkholes, suggesting that sinkholes may follow vegetation patterns similar to this type of veld. Bankenveld, or Rocky Highveld Grassland, is a transitional type of grassland found between the typical grasslands of the high inland plateau, and the bushveld of the lower inland plateau (Bredenkamp *et al.,* 1996). Its range includes the dolomite plains of Gauteng and North-West Province, so sinkholes may exhibit similar environmental characteristics to this type of veld.

Acocks interpreted Bankenveld as fire-maintained grassland, which would develop into savanna if fire was excluded (Bredenkamp *et al.,* 1996). The frequency of fire in grasslands depends on production and fire is least frequent in drier areas, but can occur annually in more moist areas (Rutherford and Westfall, 1994). Fire plays a major role in keeping Southern African grasslands treeless and trees were previously confined to fire-protected habitats within the grasslands (van Wilgen and Scholes, 1997). The intensity of fires and rate of spread depends on a number of factors, including fuel load, fuel type, fuel moisture, air temperature, relative humidity, wind speed and slope (Trollope and Potgieter, 1985; van Wilgen and Scholes, 1997). Areas outside the sinkhole may be subjected to more frequent fires, resulting in fewer trees. Grasses and bush or trees compete for growing space. Trees are favoured by the absence of fire to which they are sensitive in the early stages of establishment, and by high levels of herbivory that remove competing grasses (Stocks *et al,* 1997*)*.

Although the fire regimes experienced outside and inside the sinkholes are not known, it is possible that sinkholes experience less frequent fires, as a result of their altered physical structure. For example, immediately following the sinkhole formation, relatively little vegetative fuel may have existed within the sinkhole. This may have prevented fire from spreading into the sinkhole, providing an opportunity for woody seedlings to establish. If trees are successful in the contest between fire and herbivory, recurrent fires become more rare and fragmented as the grass fuel necessary to sustain fires becomes patchy, with most biomass residing in tree and shrub canopies (Stocks *et al,* 1997), allowing trees to further dominate inside the sinkholes.

Herbivory competes with fire for the available grass fuels and may prevent fires or reduce fire intensity in some areas, as fuels are eaten before they can burn (van Wilgen and Scholes, 1997). Cattle were observed moving through the areas surrounding the sinkholes, which would decrease the grass cover outside the sinkholes. Vegetation is influenced by herbivores in two ways, through direct consumption of plant tissues, and indirectly via nutrient cycling and soil disturbance (Hulme, 1996). Grazing management can greatly influence the composition of grassland, even though the grass plant is well adapted to defoliation such as grazing, fire or mowing (Rutherford and Westfall, 1994). It is unlikely that cattle will venture into the sinkholes as they move through the areas (herdsmen may actively prevent them from wandering near sinkholes from a safety concern). This may further contribute to the build up of plant material inside the sinkholes, particularly grass. In addition, as herbivores rarely kill the grazed plant but rather reduce its competiveness, the principal influence of herbivores is seen as plant mortality at the seed and seedling level (Hulme, 1996). The exclusion or reduction of herbivores may further enhance the establishment of seedlings inside the sinkholes.

The high rainfall recorded in areas of grassland contributes to high levels of productivity. Seasonal growth and frost curing result in high fuel loads. Less fire prone environments have been found to convert to wooded patches (O' Connor and Bredenkamp, 2004). The high numbers of woody plants observed inside sinkholes suggest that sinkholes may be less prone to fire than surrounding areas.

While, frost undoubtedly contributes to the absence of woody elements in grasslands, it is not a sufficient explanation. The overall composition of grassland is determined by numerous interactions of climatic variables, with fire and herbivory acting as secondary determinants (O' Connor and Bredenkamp, 2004).

Plants compete for resources. Light competition provides the clearest and most important examples of the complexity ability for a single resource. The major component of competitive ability for light is position relative to the source of light. Diversity can change dramatically through the course of succession, with a decrease in dominant life forms. Shade-intolerant species that initially compete successfully under high light conditions are eventually excluded by shade-tolerant species. There may be a further increase in diversity through sub-ordinant life forms, such as vines, epiphytes and herbs with high shade tolerance (Smith and Huston, 1989). A taller plant has a great advantage over a shorter competitor, regardless of the shade tolerance or other physiological properties of the smaller plant (Huston and Smith, 1987). This may give taller plants, such as trees, an advantage inside the sinkholes, allowing them to achieve higher levels of abundance inside the sinkholes compared to outside levels. The size advantage in light competition is a characteristic of individuals, not of populations or species (Huston and Smith, 1987).

It is worth mentioning here, that several deep, narrow sinkholes were observed on the property, which did not fall in the scope of this study. However, these deep sinkholes appeared to be completely dominated by woody species. It is possible that woody species are more capable of surviving in these deep sinkholes, as they are tall enough to receive sufficient sunlight to grow in comparison to shorter plants, such as grasses and forbs.

Another resource for which plants compete is water. Tree canopies intercept rainfall and redistribute water to the atmosphere through evaporation and to the ground by through fall and stem flow. Stem flow primarily improves infiltration rate and results in deeper soil wetting, leaving the surface soil unsaturated. This is likely to mainly benefit trees, whose roots penetrate the soil deeper, in comparison to other plants with shallow root systems. However, perennial grasses that have deeper root systems can also benefit from such deeper wetting (Vetaas, 1992). Once trees have become established in the sinkhole, this would serve to further benefit them in comparison to other plant species.

Succession undoubtedly results in changes in diversity. For example, under conditions of high moisture (such as those within the sinkhole), survival in high light conditions of early succession is independence of tolerance to low moisture or low light and all functional types can survive. However shade intolerant types (with intolerance for dry conditions) quickly dominate as a result of high growth rates. As light becomes reduced at ground level, the ability to survive under shaded conditions becomes more beneficial and shade-tolerant types will begin to dominate. The most mesophytic and shade tolerant species will eventually dominate under moist conditions because of their shade tolerance and size. With increasing water availability, plant density and leaf area can increase and available light at ground level decreases. Increased leaf area results in a temporal shift in species composition because initial canopy dominants cannot regenerate under reduced light conditions (Smith and Huston, 1989).

There were very low numbers of woody species outside the sinkhole in comparison to those found inside the sinkhole. Being a typically grassland area, it is expected that the area is dominated by grasses. It would appear that the sinkholes act as woody oases. Following the disturbance of sinkhole formation, there may be the potential for woody species to effectively compete with grass species, which they are not able to do outside the sinkhole, giving the woody species a chance to grow in the sinkhole. They still do not dominate within the sinkholes, but are more capable of competing with the grassy species.

The higher plant litter found inside sinkholes is likely a result of the higher levels of woody plants inside the sinkholes, which contribute to plant litter levels. The sinkhole may be more protected from wind and fire, which would reduce plant litter. Plant litter from outside the sinkhole may also be washed into the sinkhole from surface water draining into the sinkhole. Plant litter is considerably lower outside the sinkholes, due to fewer trees and possibly more frequent fire occurrences.

After plant litter, grass cover is the highest environmental variable inside the sinkholes. This can be attributed to the speed with which grasses can colonise an area. Following the sinkhole collapse, grasses are likely among the first species to grow in the sinkhole. The availability of propagules is a major determinant of the successional patterns following a disturbance (Turner *et al.*, 1998). Alternatively, in instances where no residual plants remain, succession is initiated by species from off site, through seed rain or clonal encroachment (Kotanen, 1996, Turner *et al.*, 1998). As grasses dominate outside the sinkholes, it is quite plausible that seeds and residual plants may survive the sinkhole collapse and begin to colonise the area inside the sinkhole or would be among the first species to colonise the sinkholes.

Bare ground is higher outside the sinkholes. This is likely a result of decreased plant litter from fewer trees and increased grazing levels outside the sinkholes. Canopy cover is moisture dependent in the Grassland biome and decreases with lower mean annual rainfall (Rutherford and Westfall, 1994). The study area has an annual average of 640 mm, so low canopy cover would be expected. The higher canopy cover inside the sinkholes may be a result of higher moisture availability. In addition, the increased cover of plant litter and rocks inside the sinkhole would cover the bare ground.

The higher cover of rocks inside the sinkhole may be a result of the disturbance that the area underwent during the formation of the sinkhole. Following a large, infrequent disturbance, soil disturbance or physical movement is likely to alter or even introduce new substrates (Turner *et al*., 1998). As the sinkhole forms, the soil and subsurface layers collapse, potentially exposing previously buried rocks. The outside areas have not experienced this disturbance and as such, rocks are generally embedded in the soil.

The slope and aspect of a vegetated surface strongly affects the amount of solar radiation received by that surface. Solar radiation influences ecologically critical factors of microclimate, including near surface temperatures, evaporative demand and soil moisture content (Bennie *et al*., 2008). The slopes that have formed as a result of the sinkhole collapse will thus undoubtedly influence the vegetation types that occur there.

5.2 Flora

5.2.1 Growth type

It is interesting to note that the percentage cover for grass was the highest both inside and outside the sinkholes. Grasses would be expected to dominate in the study area as it is located in the Grassland Biome. The lower grass cover inside the sinkholes may result from increased competition from other growth types, such as woody species, which showed an increase inside the sinkholes compared to cover values outside the sinkhole. The relative abundance of the herbaceous layer (grasses and forbs) and tree and shrub layer are regulated by external determinants, such as climate, soil, herbivory and fire (Vetaas, 1992). As discussed in the environmental conditions section above, these external determinants differ between outside and inside the sinkholes and undoubtedly play important roles in determining the type of plants that establish within the sinkholes.

The formation of the sinkhole may have resulted in altered conditions that allow different growth types to compete at different levels inside the sinkholes. For example, new substrates that may have formed as a result of the sinkhole collapse through soil disturbance and/or physical movement (Turner *et al*., 1998) may have allowed different growth types to exploit the new conditions. Trees often establish in depressions where there is some accumulation of water and/or organic material (Vetaas, 1992) and such depressions may have formed during the sinkhole collapse, providing woody species with the required environmental conditions to establish and better compete with other growth types.

Plant species require favourable microhabitats in order to germinate and successfully establish within a community. Certain woody species have been found to require shelter from neighbouring plants in order to establish themselves. Neighbouring plants can reduce the impacts of drought and frost on seedlings, which are the main causes of mortality for certain woody species, and allow plants to establish in areas where they were previously vulnerable to such environmental impacts (Ryser, 1993). Grasslands are subjected to frost and the combination of depressions in the sinkholes and cover from other species may provide suitable conditions that allow woody species to establish themselves within the sinkholes, which are not found outside the sinkholes.

Herbaceous plants were the second highest outside the sinkholes, in comparison to having considerably lower cover than the other growth types found inside the sinkholes. Woody, grass and succulent cover inside the sinkholes were relatively even.

5.2.2 Leaf type

As a result of their increased surface area, broad-leaved plants are more suited to low light conditions (experienced inside the sinkhole), as they can capture sufficient light, in comparison to small-leaved plants (Smith and Huston, 1989). The fine-leaved plants were found to be most abundant outside the sinkhole, in comparison to broad-leaved plants inside the sinkhole. Broad-leaved plants may be more suited to life inside the sinkhole as a result of the life strategy it has adapted to. The large surface area of the leaf is adapted to receive more sunlight, which may be beneficial inside the sinkholes where sunlight is reduced, in comparison to areas outside the sinkholes, as well as having to compete with woody species. Being able to better harvest the reduced sunlight inside the sinkholes may give broad-leaved plants an advantage.

Slope determines the exposure of vegetation to photosynthetically active and ultra-violet wavelengths (Bennie *et al*, 2008) and may influence the leaf type that establishes in that area. The increased abundance of woody species may further reduce the sunlight available for plants inside the sinkholes.

5.2.3 Seed dispersal types

The species which initially invade and establish in a site should depend, in part, on the seeds or propagules available at the time when the disturbance occurs (Kotanen, 1996). We might then expect the types of plants that establish inside the sinkhole to be those found in the area or survived the formation of the sinkhole to establish. The seed dispersal types outside the sinkhole were relatively evenly spread between wind, animal and other types. This suggests that there are no obvious barriers preventing certain types of seed dispersal. Inside the sinkholes, seeds with other dispersal types (gravity or self dispersal etc.) dominate over the other types of dispersal. This suggests that plants inside the sinkhole are likely to have occurred in the area, rather than having been transported inside the sinkhole through other means, such as wind or animal dispersal. The low levels of animal dispersed seeds indicate that fewer animals enter the sinkholes to disperse seeds in comparison to numbers outside.

5.3 Fauna

5.3.1 Vertebrates

One of the two sinkholes investigated in this study provided access to an underground cave. Another sinkhole on the property, which was not studied, provides access to another cave. Access to the caves was prohibited, so no exploration was done. However, bats will discover any opening that leads them to an underground roost and sinkholes can, thus, be considered important to the health of bat colonies (Friend, 2002).

Animals are affected by various abiotic and biotic factors, which affect their choice in habitat. Abiotic factors include temperature, water availability, wind, cover from danger and the availability of nutrients. Biotic factors refer to the location of potential mates, food, predators and parasites (Dugatkin, 2004).

Mammal species do not appear to actively avoid the sinkholes as several species were observed moving through sinkholes and the outside areas. Although mammals were found to occur significantly higher outside the sinkholes, this does not mean that sinkholes are not used by mammal species. Certain species may choose to avoid sinkholes as a result of their life strategies. For example, the yellow mongoose and ground squirrel select flat habitat that provides unobstructed views of their surroundings as predator avoidance (Apps, 2000). However, other species, such as the grey rhebok or scrub hare, may choose to enter sinkholes for increased cover or to seek shade (Vetaas, 1992).

The only mammal that was found to occur exclusively inside the sinkhole was the rodent species. While this was the only record of rodent activity in the study, and thus hardly yields any significant conclusions, it does suggest that the conditions found within the sinkhole do not exclude small mammals. The sinkhole could provide suitable habitat for rodents (increased rocks and cover) that may or may not be found outside the sinkhole. A study by Kaufman and Fleharty (1974) found that the life form of vegetation dictates the amount of cover and food available and may thus limit the distribution of small mammals more than by the presence or absence of certain plant species. Thus, even though certain plant species may not be found within sinkholes, the different vegetation types that provide suitable habitat are present, allowing small mammals to establish in the area.

Reptiles were also found to occur in significantly higher species numbers outside the sinkhole. No reptile species occurred exclusively within the sinkhole. This may result from the altered environmental conditions inside the sinkhole. More woody plants were found inside the sinkhole, reducing the amount of sunlight inside the sinkholes. This may influence the reptiles’ ability to thermoregulate. Reptiles are ectothermic and make particular choices on habitat based on the ability to facilitate thermoregulation (Adolph, 1990).

Habitat use by a particular lizard species reflects an overlap between microhabitats that are thermally suitable and those that are suited to its morphology and behavioural preferences. The thermal environment is not a strict determinant of microhabitat use by lizards: most substrates provide suitable microclimates some of the time (Adolph, 1990). However, substrates differ in the abundance and accessibility of microclimates that facilitate precise thermoregulation. Lizards selectively use microclimates where preferred body temperatures are most easily attainable (Adolph, 1990). Thus, while suitable microclimates may exist within the sinkholes, other microclimates may exist outside the sinkholes that allow for preferred body temperatures to be attained more easily and are preferred by lizard species.

Additionally, microhabitats may provide for one or more of the basic life tasks, which are to acquire food, avoid predators, cope with abiotic stresses and avoid abiotic extremes and acquire mates and reproduce. Thus while one habitat may be suitable for one such task, it may be lacking in others. As such, some lizards would accept extremely high temperatures to increase the length of their daily activity period, whereas other lizards can lower their thermal set points in cooler seasons, extending their daily activity time. These life strategies may result in their own disadvantages, for example, cooler body temperatures may reduce locomotory capacity but allow for exploitation of another resource (Anderson, 2007).

There are also several examples of ambush lizards in the same population using different microhabitats, reducing the potential for interspecific competition. Habitat shifts have also been observed by behaviourally subordinate species (Anderson, 2007). The species found inside the sinkholes may have selected that habitat as a result of reduced competition from other reptile species.

The only two recorded snake occurrences were both outside the sinkholes. Studies of several snake species have found that individual snakes actively select preferred portions of their environment, which is influenced by several factors (Reinert, 1993). It is well known that reptilian thermoregulation is more than a mere reflection of the ambient temperature and reptiles are capable of maintaining a narrow body temperature range, largely through behavioural mechanisms including differential habitat selection (Reinert, 1993). Thermal conditions may be one of the most important factors in habitat selection of many snakes as digestive efficiency, speed of locomotion, foraging efficiency and reproductive success are all related to body temperature. The range of body temperatures that a snake is able to maintain in determined, in part, through interaction between the snake and abiotic environmental variables. Environmental variables that influence the body temperatures of snakes include air temperature, substrate temperature, long- and short-wave radiation, wind velocity and humidity (Peterson *et al*., 1993).

The habitat structure of the environment also plays a role in selection of habitat for many vertebrates, including snakes. Such features may include trees and other perennial vegetation and substrate surface features, such as rocks, logs or leaf litter. The selection of appropriate foraging habitat is an obvious necessity for maintaining adequate energy intake for survival. As all snakes are predatory, the location and distribution of their prey plays an important role in habitat selection. Because of their well developed chemosensory perception, snakes are likely to detect the abundance and distribution of prey directly from proximal chemical cues in the environment and select foraging sites based upon such information (Reinert, 1993).

All terrestrial organisms face the environmental stress of desiccation. Air is a dehydrating environment and continued existence requires regular replacement of lost water. Fresh water organisms face a different problem, that of flooding the body, due to continuous influx of water. Both of these factors are important in the life of an amphibian. The skin of a frog is the major organ involved in the gain and loss of water and must be maintained in a moist condition for effective oxygen diffusion to occur. Thus, the behaviour of many amphibian species is related to the evaporative conditions in the surrounding environment. During daytime foraging the shady sites at the base of grasses or under leaves are sought. Others amphibians seek damp daytime retreats beneath stones or leaves where water can be replenished, rather than lost (Passmore and Carruthers, 1995).

Body temperature is important in frogs and affected by a complex set of factors. Like reptiles, frogs are ectothermic and depend on environmental heat sources to maintain their body temperature. Most frogs avoid exposure to high temperatures by creeping underground or by moving into shade (Passmore and Carruthers, 1995). Trees have an obvious effect on the microclimate under their canopies by intercepting solar radiation. Trees and shrubs may reduce sub-canopy solar radiation by up to 60 %, which may result in lower soil temperatures and evapotranspiration. This in turn may result in increased soil moisture content (Vetaas, 1992). The higher number of trees inside the sinkholes is likely to contribute to increased moisture content, which would be preferred by amphibian species.

All Amphibia recorded in this study were found to be common in either grassland and/or savanna. *A. angolensis* is described as living in Grassland streams and other permanent water bodies, while *S. carens* is found inhabiting Grassland vleis (Carruthers, 2001). All species require permanent water bodies to breed (Passmore and Carruthers, 1995). Amphibians are closely associated with water and moisture and it is seems likely that they were found to occur in higher numbers inside the sinkholes, as a result of cooler conditions, likely resulting from increased woody plants.

5.3.2 Invertebrates

Insecta were found to be the most abundant invertebrates followed by Arachnida and Myriapoda, both inside and outside the sinkholes. Insecta is the most abundant group of animals on the planet and so it is natural for them to be the most abundant group both inside and outside the sinkholes.

The distribution and abundance of invertebrates is influenced by climate in two ways; directly through their biology and life processes and indirectly in the determination of the nature of the habitats they occupy and their food supply (Curry, 1994). The similar numbers of Insecta found inside and outside the sinkholes suggest that the climatic conditions found outside and inside the sinkholes do not differ substantially to impact on Insecta abundance.

The small size of insects makes them sensitive to changes in temperature and moisture. The level of activity an insect can achieve depends largely on its body temperature (Unwin and Corbet, 1991). This has resulted in insects developing a wide range of physiological and behavioural mechanisms to combat the problems associated with maintaining body heat and moisture content and avoiding adverse chemical conditions, with which insects adjust to and interact with environmental conditions (Schowalter, 2000). For example, in order to maintain the desired body temperature, insects are known to alter their posture in relation to the sun or bask on leaves; the leaves absorb radiation and may reach temperatures higher than the surrounding air (Unwin and Corbet, 1991).

More Arachnida occurrences were recorded outside the sinkholes. Spiders have been found to have specific habitat preferences that dictate which species will become established and how abundant they might be (Mallis and Hurd, 2005). Numerous factors might influence why more spiders were found inside the sinkholes, including vegetation structure, physio-chemical habitat parameters, prey abundance and thermal conditions (Goldsbrough *et al.*, 2004; Mallis and Hurd, 2005). Temperature can affect many life history traits of spiders, including development rate, survival, number of moults to maturity, adult size, longevity and reproduction. Higher temperatures within a defined range can enhance growth and development for certain spiders (Goldsbrough *et al.*, 2004), as such, the areas outside the sinkholes may form warmer microclimates that are preferred by spiders.

The suitability of habitats for surface-dwelling invertebrates is greatly influenced by local features, such as the nature and density of the plant sward, presences of litter, aspect and availability of refuges from adverse conditions (Curry, 1994).

Millipedes feed on decomposing plant material and the increased plant litter inside the sinkholes may contribute to their levels of abundance. The significantly higher numbers of Myriapoda found outside the sinkholes may be a result of the possibly altered substrate inside the sinkholes, following formation of the sinkhole, as Myriapoda are commonly found beneath stones or wood in the soil.

Grazing has also been found to influence invertebrates through the alteration of botanical composition and sward structure and by altering the nature and rate of organic matter return to the soil. Effects on populations occupying the vegetation and litter are likely to be most marked but the trampling and removal of vegetation and litter may also affect the soil invertebrate populations (Curry, 1994). This removal of vegetation and litter may contribute to the increased occurrences of Myriapoda outside the sinkhole, where grazing activity is likely to be higher.

The intensity and duration of a fire determines its effect on invertebrate fauna. Under certain conditions, the litter layer may only be partially burned, which would decrease the effect on the vertebrate community. Burning is also usually conducted when the vegetation is dry and unsuitable for many invertebrate groups and while the active surface dwellers may escape the fire, the biomass of litter-dwelling and soil invertebrates can be significantly reduced by burning (Curry, 1994). This could additionally contribute to the altered distribution of Arachnida and Myriapoda occurrences observed outside the sinkholes.

5.4 Overall findings

Significant differences were found to exist between the sinkholes and the surrounding areas for the variables examined in this study. While the exact causes for these differences cannot be conclusively stated, we can attempt to provide explanations for them, which should then be examined in future studies.

The altered physical structure of the sinkholes, resulting from their formation, undoubtedly influences the types of plants and animals that exist therein. While grasses were the most abundant growth type overall, both inside and outside the sinkholes, the most notable difference was the increased abundance of woody plants inside the sinkholes. Even though grasses were still a dominant growth type inside the sinkholes, the cover of plant litter and woody species had increased substantially. This is most likely a result of the altered physical structure of the sinkholes, which favoured the establishment of woody plants compared to conditions outside the sinkholes.

The physical conditions inside the sinkhole may also provide an advantage for broad-leaved plants. Fewer broad-leaved plants were found outside the sinkholes in comparison to narrow-leaved plants. The cover of broad-leaved plants inside the sinkhole was considerably higher than the broad-leaved cover outside the sinkholes. This could be attributed to the degree of slope on which plants establish, as slope would affect the amount of solar radiation the plant is exposed to (Bennie *et al*, 2008). Additionally, the increased shade from trees inside the sinkhole would further benefit broad-leaved plants.

The slopes and physical structure of the sinkholes may also contribute to the altered abundances of animal species recorded between inside and outside the sinkholes. The recorded occurrences of mammals and reptiles were higher outside the sinkholes. In contrast, amphibians were recorded more often inside the sinkholes. These differences can be attributed to the different life traits of the various species. For example, the Yellow Mongoose prefers open habitat (Apps, 2000), as predator avoidance, resulting in their avoidance of sinkholes and the increased cover therein. In contrast, amphibians would actively seek out cover, which is increased inside the sinkholes, to reduce water loss (Carruthers, 2001), resulting in their increased abundance inside the sinkholes.

Additionally, the altered physical conditions of the sinkhole may alter wind dynamics, limiting the establishment of wind dispersed seeds. The different seed dispersal types (wind, animal and other) were similarly represented outside the sinkholes. In contrast, inside the sinkholes, the ‘other’ seed type was significantly higher than wind and animal dispersed seeds. This further suggests that sinkholes may be avoided by certain animals, which would decrease the amount of animal dispersed inside the sinkholes.

The possible exclusion of grazing, fire and frost from the sinkholes may also further benefit woody plant establishment. The grazing and fire regimes may also contribute to the slightly altered abundances of certain invertebrate groups between inside and outside the sinkholes.

While adequate for the purposes of this baseline study, several methods could be improved upon in future studies to further improve, validate and explain the results described herein. Only very basic environmental variables were recorded during this study and several additional variables undoubtedly contribute to the conditions experienced between inside and outside the sinkholes. Future studies should include measurements of temperature, rainfall, slope, humidity, wind and exposure to solar radiation as these contribute to environmental conditions. Only two sites of similar size were sampled in this study. And while the sinkholes were at least older than 25 years, their exact date of formation was unknown. The age of a sinkhole undoubtedly contributes to the level of recovery that will be observed inside a sinkhole. Difference sizes of sinkhole will also influence the degree to which environmental variables differ, with larger, deeper sinkholes varying markedly from smaller, shallower sinkholes

Arachnida and Myriapoda were recorded more often outside the sinkholes. There was no significant difference in Insecta occurrences between inside and outside the sinkholes. The invertebrate species that were found to occur exclusively either inside or outside the sinkholes were recorded in low numbers (only one or two records) and may occur in low numbers throughout the area. The majority of species that were found both inside and outside the sinkholes were recorded repeatedly. The diversity results for invertebrate fauna suggest that there is little difference between inside and outside the sinkholes and the microclimatic conditions experienced by invertebrates inside the sinkholes do not limit their occurrence.

The plants that featured in the floral composition analyses differed between overall, outside and inside values. *T. minuta* was the most frequent, abundant, dense and overall important plant for combined and inside results. It also had the highest cover inside the sinkholes. The plant with the highest cover for the combined results was *D. longiflora*.

Outside results were more varied between species; *D. longiflora* had the highest density, cover and importance values. *C. glandulosa* was the most frequent plant and *E. transvaalensis* was the most abundant plant outside the sinkholes. From this it becomes clear that species become more diverse outside the sinkholes, whereas inside the sinkholes are dominated by one species, *T. minuta*.

The consistent high scoring of Khaki weed inside the sinkholes is a concern, as South Africa has a long history of problems with invasive alien species (Richardson and van Wilgen, 2004). The floral diversity index suggested that a particular species may dominate inside the sinkholes. This is likely to be Khaki weed as it was the species with the highest frequency, abundance, density and cover. The majority of Khaki weed records were seedlings. The Grassland Biome has been extensively invaded, particularly by alien tree species along river banks. The most damaging alien plants transform ecosystems through the excessive use of resources (water, light and oxygen), the addition of nitrogen, altering fire regimes, influencing soil regimes and the accumulation of litter (Richardson and van Wilgen, 2004). The potentially cooler and moister conditions inside sinkholes may make them more susceptible to the establishment of alien species.

The multivariate analysis showed a certain degree of separation between inside and outside quadrats, suggesting consistent differences between the environmental variables found therein. Few species align themselves with a particular environmental variable or a certain quadrat, suggesting that different environmental variables contribute to the establishment of species. Alternatively, environmental variables not included in this study may also contribute to the establishment of species.

While the total number of recorded species inside the sinkholes was lower than outside values for both fauna and flora, certain species were observed as occurring either exclusively inside or exclusively outside the sinkholes. This suggests that both environments (inside and outside) provide habitats that are suited or preferred for the establishment of certain species, both plant and animal.

6. CONCLUSION

From this study it would appear that while sinkholes provide an environment that is altered to the surrounding outside conditions, they are likely to provide an environment that is suitable for the establishment of numerous species and may be preferred by certain species. Mosses and ferns, typically moisture loving plants, were found inside the sinkholes, while absent outside the sinkholes. Woody species were also significantly more abundant inside the sinkholes compared to the surrounding areas, suggesting environmental conditions inside the sinkholes are better suited for the establishment of such species. In addition, amphibians were more abundant inside the sinkholes, which require a moist environment.

Thorough knowledge of the ecology of the species is necessary in order to fully understand the how and why of habitat selection. This would involve intensive behavioural observation and often requires experimentation (Reinhert, 1993). This study can only suggest plausible explanations as to why species were observed either inside or outside the sinkholes and should serve as the basis for future studies that will provide further insight into the role that sinkholes play in habitat selection.

This study was limited in the amount of environmental variables studied and the degree of detail in which they were examined. More environmental variables should be studied and in greater detail in future studies. For example, the effect of slope plays an important role in the amount of radiation received by plants (Bennie *et al*, 2008) and this is likely to influence the types of plants that establish on the slopes of the sinkholes. The degree of slope could be further studied to determine the effect on rate of establishment, the type of plant that establishes and the possible resultant impact on animal species. Reptiles, being endothermic, may also be influenced by the amount of solar radiation received inside the sinkholes.

The age of sinkholes is undoubtedly an important factor in determining the stage of succession and level of rehabilitation success and should be included in further studies. A study following the successional transition from the start of a sinkhole formation would also be useful in determining rate of succession and time taken for recovery.

In addition, detailed studies examining the differences in environmental parameters, such as temperature, wind speed, moisture, soils, grazing and fire regimes would provide further insight into the differences observed between sinkholes and the surrounding areas.

Several smaller sinkholes (1 m^3) were observed in the area, which appeared to be dominated by only one or two (weedy) species. In addition, several very deep sinkholes (20 m) appeared to be dominated only by trees. It is possible that such woody species are among the only species capable of surviving in such deep sinkholes, as a result of low light conditions. Further research could provide insight into how the size and depth of sinkholes influence the type of species that establish therein.

The policy of dewatering the dolomitic reservoirs has numerous detrimental environmental consequences. However, it has contributed to the great economic benefit of the mines and to the safety of workers (Swart *et al.*, 2003b). It is only fitting then, that the mining companies accept responsibility for the rehabilitation of sinkholes.

In instances where the formation of a sinkhole poses a direct risk to human safety and/or infrastructure, it is undoubtedly best practice to fill and stabilise the sinkhole, with appropriately engineered designs as recommended in several studies, such as Gutiérrez *et al*. (2008) and Zhou and Beck (2008). However, in instances where sinkholes pose no direct threat, it may be best to allow natural rehabilitation. This would not only save mining companies potentially millions of dollars, but it also allows new environments to persist that contribute to overall ecosystem functioning.

Refilling the sinkholes such as those studied herein would undoubtedly change the environment to which plants and animals have adapted and while the majority of species would continue to occur outside the sinkhole, certain species were found only inside the sinkholes. In addition, during the refilling operations, small animals that inhabit the sinkholes may be killed unless they are relocated prior to refilling, which would incur additional costs.

Alien plants impact on the surrounding environment and have been found to reduce the diversity of grassland birds, through the conversion of grasslands to strands of alien trees (Richardson and van Wilgen, 2004). As a precaution, it is recommended that sinkholes on mining property are monitored on a regular basis for alien vegetation, such as Khaki weed, and any alien vegetation should be removed from the sinkholes.

The difference in diversity found between sinkholes and their surrounding environment varies in application. From an ecological perspective, the slight reduction in diversity inside sinkholes only becomes of concern if sinkholes cover a large proportion of a particular area - resulting in a fundamental change in ecosystem composition. With regard to rehabilitation of sinkholes from a mine management perspective, the altered diversity found within these particular sinkholes does not appear to warrant complete rehabilitation. The associated costs and further impact on an already disturbed site are not necessary given the altered condition of the sinkhole. The sinkhole has formed a natural environment, which experiences altered physical and climatic conditions to which plants and animals have adapted.

However, these observations are based on only two sinkhole sites, of unknown age. Other sinkholes may not recover to similar states observed in this study and additional studies should be conducted to determine what degree age, size, location and physical attributes contribute to the recovery of a sinkhole.

This initial survey suggests that sinkholes, while supporting slightly reduced numbers of species and individuals, do not necessarily present reduced functionality. No functional groups (producers, consumers, decomposers, etc.) were significantly reduced inside the sinkholes. More studies are required to understand the causes of the differences found between sinkholes and the manner in which these differences affect the species found within sinkholes.

The major life support systems of the planet do not seem to have worked in a substantially different way because fewer species were involved in the processes (Lawton and Brown, 1993). This suggests that even less diverse systems, such as the sinkholes in this study, with their reduced species numbers, are capable of carrying out the various ecosystem processes and undoubtedly continue to support life.

APPENDIX A: COMPLETE LIST OF PLANT SPECIES

Scientific name	Common name	No. of individuals		Percentage		Growth type	Leaf type	Seed type
		Outside	Inside	Outside	Inside			
Acalypha caperonioides	-	0	1	0	100	Woody	Narrow	Animal
Aloe davyana	-	0	3	0	100	Succulent	Broad	Wind
Anthospermum rigidum	-	2	0	100	0	Herb	Narrow	Wind
Aristida stipitata	Long-awned grass	1	0	100	0	Grass	Narrow	Wind
Artemisia afra	Wild wormwood	0	1	0	100	Woody	Broad	Wind
Asparagus setaceus	Asparagus fern	1	9	10	90	Woody	Narrow	Animal
Bidens pilosa	Blackjack	0	1	0	100	Herb	Broad	Animal
Bulbine angustifolia	-	1	1	50	50	Herb	Narrow	Wind
Celtis africana	White stinkwood	0	56	0	100	Woody	Broad	Animal
Chaemecrista stricta	-	11	0	100	0	Herb	Narrow	Wind
Chaetacantus glandulosa	-	29	4	88	12	Herb	Broad	Animal
Chamaesyce (Euphorbia) maculata	-	8	4	67	33	Woody	Narrow	Animal
Cheilanthes hirta	Hairy lip fern	0	21	0	100	Woody	Narrow	Wind
Clutia affinis (seedling)	Water lightning-bush	0	30	0	100	Woody	Narrow	Animal
Commelina erecta	-	1	9	10	90	Herb	Narrow	Animal
Conyza chilensis	-	0	9	0	100	Succulent	Narrow	Wind
Conyza gouanii	-	3	2	60	40	Herb	Narrow	Wind
Corchorus asplenifolius	-	9	6	60	40	Succulent	Narrow	Wind
Crabbea acaulis	-	2	1	67	33	Herb	Broad	Wind
Crabbea angustifolia	-	3	1	75	25	Herb	Narrow	Wind
Cyanotis speciosa	Doll's powderpuff	13	1	93	7	Herb	Narrow	Animal
Cyperus margaritaceus	-	2	0	100	0	Herb	Narrow	Animal
Cyperus rupestris	-	6	0	100	0	Herb	Narrow	Animal
Dianthus mooiensis	Wild pink	1	0	100	0	Herb	Narrow	Wind
Dichondra micrantha	-	0	45	0	100	Herb	Broad	Animal
Digitaria longiflora	-	8	6	57	43	Herb	Narrow	Other
Diospyros lycioides subsp. Guerkei	Bloubos	2	1	67	33	Woody	Broad	Animal
Elionurus muticus	Sour grass	20	1	95	5	Grass	Narrow	Wind
Eragrostis racemosa	Narrow-heart love grass	0	1	0	100	Grass	Narrow	Animal
Eragrostis superba	Saw-tooth love grass	1	0	100	0	Grass	Narrow	Animal
Euryops transvaalensis	-	30	0	100	0	Woody	Narrow	Wind
Eustachys paspaloides	Fan grass	1	0	100	0	Grass	Narrow	Wind
Gazania krebsiana	Botterblom	2	0	100	0	Herb	Narrow	Wind
Gomphocarpus fruticosus	Milkweed	0	1	0	100	Woody	Narrow	Wind
Grewia flava	Raisin bush	0	3	0	100	Woody	Broad	Other
Helichrysum caespititium	Speelwonderboom	4	0	100	0	Herb	Narrow	Animal
Helichrysum callicomum	-	0	2	0	100	Herb	Narrow	Animal
Helichrysum nudifolium	Hottentot's tea	2	3	40	60	Herb	Narrow	Animal
Hermannia transvaalensis	-	6	0	100	0	Herb	Broad	Animal
Hypoxis acuminata	-	0	3	0	100	Herb	Narrow	Other

Scientific name	Common name	No. of individuals		Percentage		Growth	Leaf	Seed
Indigophera hilaris	Red indigo bush	7	0	100	0	Woody	Narrow	Wind
Ipomoea crassipes	Leafy-flowered Ipomoea	3	0	100	0	Herb	Broad	Animal
Kohautia cycanchica	-	2	3	40	60	Herb	Narrow	Animal
Kylinga alba	Witbiesie	12	2	86	14	Herb	Narrow	Other
Ledebouria ovatifolia	-	3	0	100	0	Herb	Broad	Wind
Leucas martinicensis	-	0	1	0	100	Woody	Narrow	Animal
Lotononis calycina	Hairy lotononis	2	0	100	0	Herb	Broad	Animal
Melinis nerviglumis	Bristle leaf red top	2	12	14	86	Grass	Narrow	Wind
Menodora africana	Balbossie	2	0	100	0	Herb	Narrow	Animal
Nidorella anomala	-	25	0	100	0	Herb	Narrow	Other
Nidorella hottentotica	-	23	0	100	0	Herb	Narrow	Other
Ocimum waterbergensis	-	2	0	100	0	Herb	Narrow	Animal
Ophioglossum polyphyllum	-	9	0	100	0	Herb	Narrow	Animal
Opuntia ficus-indica	Sweet prickly pear	0	2	0	100	Herb	Broad	Other
Oxalis obliquifolia	Sorrel	3	8	27	73	Succulent	Broad	Other
Oxygonum dregeanum	-	2	0	100	0	Herb	Narrow	Animal
Oxygonum sinuatum	Dubbeltjie	1	0	100	0	Herb	Broad	Animal
Polygala hottentotta	Small purple broom	1	0	100	0	Herb	Narrow	Animal
Pseudognaphalium oligandrum	-	6	3	67	33	Herb	Narrow	Animal
Pygmaeothamnus zeyheri	Sand apple	6	0	100	0	Woody	Broad	Animal
Rhus pyroides	Common wild currant	1	5	17	83	Woody	Broad	Animal
Rhus rigida	Kliptaaibos	0	1	0	100	Woody	Broad	Animal
Rotheca hirsuta	-	2	0	100	0	Herb	Broad	Animal
Scadoxus puniceus	Red paintbrush	0	3	0	100	Herb	Broad	Animal
Senecio consanguineus	Starvation senecio	2	3	40	60	Herb	Narrow	Wind
Senecio lydenburgensis	-	15	7	68	32	Herb	Narrow	Wind
Setaria sphacelata var. sphacelata	Small creeping foxtail	9	3	75	25	Grass	Narrow	Other
Sida ternata	-	0	1	0	100	Woody	Broad	Animal
Sonchus dregeanus	-	0	2	0	100	Herb	Narrow	Wind
Spermacoce natalensis	-	0	1	0	100	Herb	Narrow	Animal
Stoebe vulgaris	Bankrupt bush	3	6	33	67	Woody	Narrow	Animal
Tagetes minuta (seedlings)	Khaki weed	8	989	1	99	Herb	Narrow	Other
Teucrium trifidum	Koorsbossie	1	0	100	0	Herb	Narrow	Animal
Vernonia oligacephala	Bitterbossie	10	0	100	0	Woody	Broad	Wind
Wahlenbergia squamifolia	-	1	1	50	50	Herb	Narrow	Animal
Waltheria indica	Meidebossie	9	2	82	18	Woody	Broad	Animal
Ziziphus zeyheriana	Dwarf buffalo-thorn	12	1	92	8	Woody	Broad	Animal

APPENDIX B: COMPLETE LIST OF INSECT SPECIES

Order	Species	Outside	Inside
Blattodea	*Blattodea sp.*	✗	✓
	Deropeltis erythrocephala	✗	✓
Coleoptera	*Adoretus ictericus*	✗	✓
	Anthia thoracica	✓	✗
	Ceroplesis thunbergi	✗	✓
	Cheilomenes lunata	✓	✗
	Coleoptera sp. 1	✓	✗
	Coleoptera sp. 2	✓	✓
	Coleoptera sp. 3	✓	✓
	Coleoptera sp. 4	✓	✓
	Coleoptera sp. 5	✓	✓
	Coleoptera sp. 6	✓	✓
	Coleoptera sp. 7	✓	✓
	Coleoptera sp. 8	✓	✗
	Coleoptera sp. 9	✗	✓
	Coleoptera sp. 10	✗	✓
	Coleoptera sp. 11	✓	✗
	Coleoptera sp. 12	✓	✗
	Coleoptera sp. 13	✗	✓
	Coleoptera sp. 14	✓	✓
	Coleoptera sp. 15	✓	✗
	Coleoptera sp. 16	✓	✓
	Coleoptera sp. 17	✓	✗
	Curculionidae family	✓	✓
	Cyrtothyrea marginalis	✓	✗
	Garreta nitens	✓	✓
	Himatismus sp.	✗	✓
	Histeridae family 1	✓	✗
	Histeridae family 2	✓	✓
	Hydrophilidae family	✓	✓
	Lycidae family larva	✓	✓
	Mylabris oculata	✓	✗
	Psammodes sp.	✓	✓
	Staphylinidae family	✓	✓
	Staphylinidae family 2	✓	✓
Hemiptera	*Coridius nubilis*	✗	✓
	Hemiptera sp. 1	✓	✗
	Hemiptera sp. 2	✓	✓
	Hemiptera sp. 3	✓	✗

Order	Species	Outside	Inside
	Hemiptera sp. 4	✓	✗
	Hemiptera sp. 5	✓	✗
	Hemiptera sp. 6	✓	✗
	Hemiptera sp. 7	✗	✓
	Hemiptera sp. 8	✓	✓
	Hemiptera sp. 9	✓	✗
	Hemiptera sp. 10	✓	✗
	Hemiptera sp. 11	✓	✗
	Hemiptera sp. 12	✗	✓
	Hemiptera sp. 13	✗	✓
	Nezara viridula	✓	✗
	Pentatomidae family	✗	✓
	Spilostethus pandurus	✗	✓
	Veterna sp.	✓	✓
Hymenoptera	*Anoplolepsis custodiens*	✓	✓
	Apis mellifera	✓	✓
	Chrysomya albiceps	✗	✓
	Corinnidae family	✗	✓
	Diptera 1	✗	✓
	Diptera 2	✓	✗
	Diptera 3	✗	✓
	Hymenoptera 2	✗	✓
	Hymenoptera 3	✓	✗
	Hymenoptera 4	✗	✓
	Messor capensis	✓	✓
Insecta	*Larva sp.*	✓	✗
Lepidoptera	*Eurema hecabe solifera*	✓	✗
	Lepidoptera larva 1	✗	✓
	Lepidoptera larva 2	✓	✓
	Lepidoptera larva 3	✓	✓
	Pontia helice helice	✓	✗
	Tarucus sybaris	✓	✗
Mantodea	*Mantodea sp.*	✓	✗
	Sphodromantis gastrica	✗	✓
Orthoptera	*Acrididae family*	✗	✓
	Dictyophorus spumans	✓	✗
	Gryllus bimaculatus	✓	✓
	Lamarckiana sp.	✓	✗
	Macrotermes natalensis	✓	✓
	Orthoptera sp.	✓	✓
	Phymateus morbillosus	✓	✗
	Platygryllus sp.	✓	✓
Phasmatodea	*Bacillidae family*	✓	✓

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