An urban ecological synthesis of socio-ecological systems dynamics in Potchefstroom, South Africa

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Abstract

As rural populations decrease and cities expand, the importance of urban ecological research becomes globally significant. Urban ecology seeks to understand the complex relationships between human settlements and their ecological contexts in an attempt to ensure sustainable futures. The discipline of urban ecology is at the forefront of the conflict between human perceptions, economy, and politics. Despite numerous studies conducted in urban areas in South Africa, no one city has yet synthesized all the amassed research conducted within its city limits. A shortage of detailed ecological data, therefore, led to an extensive study of urban open spaces in some cities of the North-West Province encompassing multiple disciplines. Consequently, this study attempts to consolidate and evaluate all the existing urban ecological research in South Africa and specifically, in the city of Potchefstroom.

Firstly, a comprehensive overview of South African urban ecological literature discussing the early development, research themes and the future of urban ecology in South Africa was carried out. Three hundred and fourteen publications were reviewed and categorized into the following research themes: physical environment, biodiversity, management, conservation, planning, human needs, sustainability, public participation, ecosystem services, and resilience. Secondly, as researchers have long been interested in studying and explaining patterns of biodiversity in natural and anthropogenic landscapes, many theories have been proposed on the drivers of these patterns and numerous studies compare current land-use effects with biotic assemblages. However, a much-neglected perspective in urban ecological research is the impact of the history of the landscape. Consequently, the second paper investigated the possible time lags in the response of temperate natural grasslands to urbanization and the factors driving these changes. Thirdly, a study of the temporal vegetation dynamics of urban grasslands in Potchefstroom over a 17-year period was carried out. Open grasslands, woody vegetation sites, and vacant lots were resurveyed within the city limits. The potential change in species richness and abundance of species, and the differences in species composition between these three habitat types were compared. Lastly, the fourth paper synthesizes all the relevant existing interdisciplinary research carried out of urban open spaces in Potchefstroom. This is evaluated against municipal governance and management strategies, environmental law, public opinion and the steep spatially organized socio-economic gradient found in Potchefstroom, informing the progress towards a sustainable, liveable city.

The results of the literature study indicated that there were various gaps within each theme that need to be addressed in future. In the study on the effects of urbanization history on observed vegetation patterns, the woody vegetation showed important time lags in the response of indigenous species richness to urbanization. The measures altitude and the road network density of natural areas were the most frequent predictors of species richness. Results of the temporal vegetation dynamics of urban grasslands indicated that in the relatively short 17 year period most vegetation diversity indices changed significantly, specifically a significant decrease in indigenous species richness of both grasslands and woody communities were noted. The synthesis of all the studies carried out in Potchefstroom revealed an impressive number of studies carried out, however most of the biodiversity groups were represented by a single investigation only. Evaluating the results with the IDP revealed than much of the known ecological information in Potchefstroom remains undiscovered by municipal policymakers. Moreover, proposed future development is planned for some of the highest biodiversity sites.

This synthesis and the subsequent identification of the gaps in our understanding and research themes will allow a purposeful and informed advancement of the science of urban ecology in South Africa and the contribution thereof towards advancing urban ecology globally. In addition, the history of urbanization affects contemporary vegetation assemblages in urban areas indicating potential extinction debts. Moreover, the significant decreases in indigenous species richness of woody and grassland sites have important consequences for urban grassland conservation in South Africa. Subsequently, the knowledge and the identification of research gaps allow decision makers in Potchefstroom to plan for sustainable future solutions and for this city to emerge as a leading role player in the South African urban ecological context. The results of this thesis could be a substantial practical aid in policy and management strategies furthering decision makers in the pursuit of the elusive goal of developing sustainable cities.

Keywords: Urban ecology, grassland, time lags, biodiversity, temporal change.

Uittreksel

Stedelike ekologiese navorsing word wêreldwyd meer betekenisvol soos die landelike bevolking krimp en stede groei. Stedelike ekologie het ten doel om die komplekse verwantskappe tussen menslike nedersettings en hul ekologiese kontekste te verstaan in ’n poging om ’n volhoubare toekoms te verseker. Die dissipline van stedelike ekologie is aan die voorpunt van die konflik tussen menslike persepsies, ekonomie en politiek. Ten spyte van talle studies wat in Suid-Afrikaanse stedelike gebiede gedoen word, is daar nog nie een stad waarin al die navorsing wat binne die grense van die stad gedoen is saamgevat het nie. Daarvolgens, het ’n tekort aan volledige ekologiese data gelei tot ’n omvattende studie van stedelike oop ruimtes in sommige stede in die Noordwes provinsie wat verskeie dissiplines insluit. Gevolglik, poog hierdie studie om al die bestaande stedelik ekologiese navorsing wat in Suid-Afrika en spesifiek Potchefstroom gedoen is te konsolideer en te evalueer.

Eerstens is ’n breedvoerige oorsig gedoen oor die Suid-Afrikaanse stedelik ekologiese literatuur wat die vroeë ontwikkeling, benaderings en die toekoms van stedelike ekologie in Suid-Afrika bespreek. Driehonderd en veertien publikasies is hersien en ingedeel volgens die volgende benaderings: fisiese omgewing, biodiversiteit, bestuur, bewaring, beplanning, menslike behoeftes, volhoubaarheid, gemeenskapsbetrokkenheid, ekosisteemdienste en veerkragtigheid. Tweedens, omdat navorsers lank al geïnteresseerd is in die bestudering en verklaring van patrone van biodiversiteit in natuurlike en antropogeniese landskappe is daar al baie teorieë voorgestel oor die drywers van hierdie patrone en talle studies vergelyk die invloed van huidige grondgebruike met biotiese groeperings. Nietemin, die impak van die landskapsgeskiedenis as perspektief is baie afgeskeep in stedelik ekologiese navorsing. Vervolgens het die tweede manuskrip die moontlike tydvertragings ondersoek in die reaksie van gematigde natuurlike grasvelde op verstedeliking en die faktore wat hierdie veranderinge aandryf. Derdens, is ’n studie van langtermyn plantegroei dinamika van stedelike grasvelde in Potchefstroom oor ’n tydperk van 17 jaar gedoen. Plantegroei opnames is in oop grasvelde, gebiede met houtagtige plantegroei en oop erwe binne die stadsgrense herhaal. Die moontlike veranderinge in spesierykheid en volopheid van spesies en die verskille in spesiesamestelling tussen die verskillende habitat tipes is vergelyk. Laastens, kombineer die vierde manuskrip al die relevante bestaande interdissiplinêre navorsing wat in die stedelike oop ruimtes van Potchefstroom gedoen is. Dit word gevalueer teenoor munisipale bestuurstrategieë, omgewingswetgewing, die opinie van die gemeenskap en die steil ruimtelik georganiseerde sosio-ekonomiese gradiënt wat in Potchefstroom aanwesig is, wat die onderbou verskaf vir die bevordering van ’n volhoubare leefbare stad.

Die resultate van die literatuurstudie het aangedui dat daar verskeie leemtes binne elke benadering was wat in die toekoms aangespreek moet word. In die studie van die effek van verstedelikingsgeskiedenis op waargenome plantegroei patrone, het die houtagtige plantegroei belangrike tydvertragings getoon in die reaksie van inheemse spesierykheid op verstedeliking. Die metings van hoogte bo seespieël en die padnetwerk digtheid van natuurlike gebiede het spesierykheid die beste voorspel. Die resultate van die langtermyn plantegroei dinamika van stedelike grasvelde het aangedui dat in die relatiewe kort tydperk van 17 jaar meeste van die plantegroei diversiteitsindekse merkwaardig verander het, veral ’n betekenisvolle afname van inheemse spesierykheid van beide grasvelde en houtagtige gemeenskappe is aangetoon. ’n Sintese van al die studies wat in Potchefstroom gedoen is, het onthul dat ’n indrukwekkende aantal studies gedoen is, maar dat meeste van die biodiversiteitsgroepe slegs deur ’n enkele opname verteenwoordig is. Die evaluering van die resultate saam met die geïntegreerde ontwikkelingsplan het onthul dat baie van die bestaande ekologiese inligting in Potchefstroom nog nie deur munisipale beleidmakers ontdek is nie.

Boonop word voorgestelde toekomstige ontwikkeling beplan in van die gebiede met die hoogste biodiversiteit.

Hierdie sintese en die daaropvolgende identifisering van die leemtes in ons insig en navorsingsbenaderings sal ’n doelgerigte en ingeligte bevordering van die wetenskap van stedelike ekologie in Suid-Afrika meebring en die bydrae daarvan sal stedelike ekologie wêreldwyd bevorder. Meer nog, die geskiedenis van verstedeliking beïnvloed huidige plantegroei groeperings in stedelike gebiede wat potensiële uitwissingsskuld aandui. Boonop het die betekenisvolle afname in inheemse spesierykheid van houtagtige en grasveld gebiede belangrike gevolge vir bewaring van stedelike grasvelde in Suid-Afrika. Vervolgens laat die kennis en identifikasie van navorsingsleemtes besluitnemers in Potchefstroom toe om te beplan vir volhoubare oplossings vir die toekoms en vir hierdie stad om te verrys as ’n toonaangewende rolspeler in die Suid-Afrikaanse stedelik ekologiese konteks. Die resultate van hierdie tesis kan ’n substansiële praktiese hulpmiddel wees in beleid- en bestuurstrategieë om besluitnemers te help in die nastrewing van die ontwykende doelwit van die ontwikkeling van volhoubare stede.

Sleutelwoorde: Stedelike ekologie, grasveld, tydvertragings, biodiversiteit, verandering oor tyd.

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Soli Deo Gloria

"Want by U is die fontein van die lewe,
in U lig sien ons die lig"
Ps 36:9

Preface

This is to state that I, Marié J du Toit, have chosen the article format for submitting my thesis.

The work was done by myself, Marié J du Toit, with editing done and suggestions given by Prof SS Cilliers as promoter of my PhD. Dr JD Kotze, as co-author of paper 2, performed the R statistical analyses.

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The papers have been prepared for submission to the following journals:

Paper 1: Urban Ecosystems
http://www.springer.com/life+sciences/ecology/journal/11252?detailsPage=aboutThis
Paper 2: Landscape Ecology
http://www.springer.com/life+sciences/ecology/journal/10980?detailsPage=press
Paper 3: South African Journal of Botany
http://www.elsevier.com/journals/south-african-journal-of-botany/0254-6299/guide-for-authors
Paper 4: Landscape and Urban Planning
http://www.elsevier.com/journals/landscape-and-urban-planning/0169-2046/guide-for-authors

Text is, however, not in preferred font and size of journals for sake of uniformity of thesis.

The reference style used for the General Introduction and General Conclusions is according to the journal *Landscape Ecology.*

Permissions:

I, Sarel S Cilliers, hereby give my permission that Marié J du Toit may submit the manuscript(s) for degree purposes.

I, Johan D Kotze (co-author of Paper 2), hereby give my permission that Marié J du Toit may submit the manuscript for degree purposes.

Acknowledgement of papers: (omitted from papers for ease of reading)

Paper 1, 2 and 4:
We would like to thank the National Research Foundation (NRF) for financial assistance towards the studies of MJDT.

Paper 3:
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General Introduction

In a recent news article in *Nature,* Corbyn (2010) stated that most ecologists ignore urban landscapes as viable research areas. However, the importance of urban ecological research could not have been better emphasized than the statement by the UN Secretary-General that the "*future of humanity lies in cities*" (Annan 2002). Likewise, Wu (2014) stated that "*unlike many other fields of study that wax and wane in their popularity, the study of urban ecology and sustainability will most likely stay "hot" because our present and future depend on it*". Much research has been amassed on urban ecological issues and great leaps have been made in extending what are known of urban environments (e.g. Alberti 2008; Marzluff et al. 2008; Niemelä 2011; Pickett et al. 2011; Wu 2014). However, researchers call for a more comprehensive understanding of the structure and functioning of urban ecosystems (McDonnell et al. 2009) as well as the development of confirmed generalizations (McDonnell and Hahs 2013; Pickett et al. 2011). The challenge was unambiguously stated by Alberti (2008): *"...the mechanisms through which urbanization patterns affect ecosystem processes are still virtually unknown. Nor do we know how biophysical patterns and processes and their dynamic changes affect human choices regarding their spatial arrangement on the landscape. We do not know how urban ecosystems evolve through the interactions between human and ecological processes, nor do we know what factors control their dynamics. Although a substantial body of urban research has focused on the dynamics of urban systems - their sociology, economics, ecology, and policies - these diverse dimensions have yet to be synthesized into one coherent theoretical framework."*

Furthermore, North American and European studies are disproportionately represented in urban ecological literature, much less is published about urban areas south of the equator—especially in developing countries. In this regard, South African researchers stand out as one of the leading contributors to urban ecological research in the developing countries of the global South. Moreover, globally highly regarded publications have been published on research carried out in especially Cape Town and Durban (e.g. Carmin et al. 2012; Ernstson 2013; Ernstson et al. 2010; Roberts 2008). A distinctive urban spatial organizational legacy—due to political dispensations of the past— in combination with rich and diverse biodiversity, make South Africa a unique setting in which to study the dynamics of urban environmental interactions. Increasing urbanization is a major threat to biodiversity in South Africa (Cilliers et al. 2004; Holmes et al. 2012; O'Connor and Kuyler 2009). South African cities are witnessing an unprecedented increase in the number of squatting and informal settlements on the urban fringe as people flock to cities for the hope of employment opportunities.

Despite roughly two decades of urban ecological research in South Africa, no comprehensive review has yet been carried out. However, in a recent Special Issue on Cape Town in the journal, *Ecology and Society*, Cilliers and Siebert (2012) compiled an overview of the research carried out in Cape Town in the context of other South African studies. The first paper in this thesis greatly expands on this first review of urban ecological research in South Africa. Hard-pressed decision-makers often require scientists to provide instant answers to environmental problems. Researchers are therefore increasingly relying on existing information to supplement detailed time consuming investigations. Furthermore, despite numerous studies conducted in urban areas in South Africa, no one city has yet synthesized all the amassed research conducted within its city limits. Potchefstroom, in the North-West Province, is an example of such a city. A shortage of detailed ecological data for urban areas in South Africa led to an extensive study of urban open spaces in some cities of the North-West Province (e.g. Cilliers 1998; Jansen van Rensburg 2010; Pelser 2006; Putter 2004; Smith 2004; van Wyk et al. 1997). These studies encompass disciplinary research in zoology, botany, and microbiology; including interdisciplinary research incorporating aspects of geography, planning, and social sciences. They were carried out as part of a bigger overarching urban ecology project conducted in the North-West Province with the focus on urban and settlement ecology aimed towards an integrated approach to natural and social processes in sustainable environments. No real effort has as yet been made to consolidate and evaluate all the existing research in the city of Potchefstroom. The current study will attempt to fill this gap.

Part of the above-mentioned project was an extensive vegetation classification study of the urban open spaces of Potchefstroom in 1995-6 (Cilliers et al. 1998; Cilliers and Bredenkamp 1998, 1999a, b, 2000; Cilliers et al. 1999). These surveys have allowed the unique opportunity to resample some of the vegetation sites in 2012 after a 17-year period. Few researchers have the luxury of comprehensive historical datasets, especially in urban areas. Possession of such data allows rare and unique insights into the long-term effects of urbanization on its local and surrounding vegetation. Results obtained from these type of comparisons can strengthen theories and assumptions based on typical one-off field sampling studies. Moreover, temporal data allows the quantification of legacy effects on current vegetation patterns. Magnuson (1990) states that "*in the absence of the temporal context provided by long-term research, serious misjudgements can occur not only in our attempts to understand and predict change in the world around us, but also in our attempts to manage our environment*". Globally, urban legacy studies are rare. Moreover, no such study has yet been carried out in South Africa. The overall aim will be to attempt to contribute towards the extension of ecological theory in the understanding of the human impacts on biodiversity in urban environments. In addition, the proposed study will be a significant contribution to urban ecological research in South Africa. Observed patterns and processes operating in urban environments will be identified and described. By finding gaps in the existing data, further research projects could be stimulated on relevant and under researched topics.

The discipline of urban ecology is at the forefront of the conflict between human perceptions, economy, and politics. Urban nature conservation in South Africa desperately needs this type of research. By simultaneously addressing complex social issues, more weight will be added to the importance of biodiversity and, therefore, the acceptance of nature conservation by the broader community. Research in urban and grassland nature conservation will be contributed to in a meaningful way, confidently initiating human perception changes towards nature, especially those found in and around cities. Successfully linking social and natural systems in a practically applicable way may also convince decision-makers to pay attention, thereby advancing towards sustainable solutions in urban environments. The results of this thesis could be a substantial practical aid in policy and management strategies furthering decision-makers in the pursuit of the elusive goal of developing sustainable cities.

Aims of the thesis

General objective:
An urban ecological investigation on the state of the science in South Africa with the specific focus on the socio-ecological interactions and dynamics in Potchefstroom, South Africa.

Specific objectives:

1. To do a comprehensive review of urban ecological research in South Africa and identify gaps in the existing research approaches.
2. To determine the effect of the landscape history on the observed vegetation patterns and to quantify potential ecological legacies.
3. To quantify the temporal vegetation dynamics of the Potchefstroom urban area over a 17-year period.

4. To attempt an interdisciplinary spatial integration and synthesis of all the relevant existing urban ecological research carried out in Potchefstroom to date.

Study area

The study was conducted in the city of Potchefstroom (26˚ 42′ 53′′ S; 27˚ 05′ 49′′ E) and its immediate natural surroundings, situated in the North-West Province of South Africa (Figure 1). The city covers a 55 km^2 area with a population of approximately 250 000 (www.potch.co.za). The mean annual rainfall is 600mm that it receives predominantly in the summer months (October to March), with average temperatures ranging between 30°C and 0°C and frequent frost in winter (www.weathersa.co.za). The central part of the city is laid out along the western banks of the Mooi River on a flat plain, the western side of the city consisting of the residential areas of Ikageng, the Ikageng extension, Mohadin, and Promosa are situated amongst a series of small hills and ridges (Figures 1 and 2).

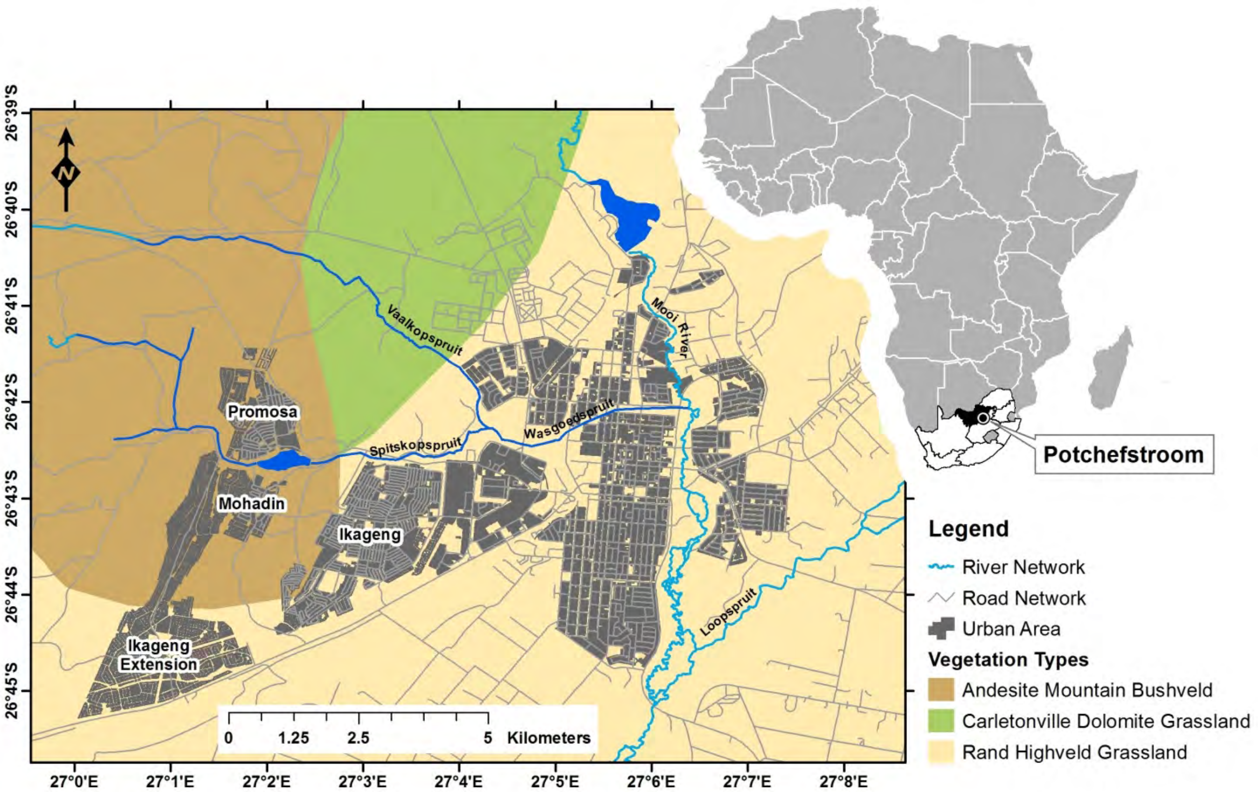

Figure 1: Map of Potchefstroom showing the vegetation types according to Mucina and Rutherford (2006) found in the study area, as well as an inset map indicating the location of Potchefstroom in the North-West Province, South Africa and in Africa.

Potchefstroom is situated in the Grassland biome at the confluence of three vegetation types, namely the Rand Highveld Grassland, Carletonville Dolomite Grassland and the Andesite Mountain Bushveld (Mucina and Rutherford 2006) (Figure 1). The latter being Savanna elements as found on the hills, rocky outcrops and ridges in the area (Figure 2). Figure 3 illustrates examples of grasslands and woody grassland vegetation in the study area. Dominant graminoids in the study area include: *Themeda triandra* , *Eragrostis chloromelas, Cynodon dactylon, Digitaria eriantha, Panicum maximum, Heteropogon contortus*, and *Setaria sphacelata* var. *torta*. Dominant shrubs: *Asparagus suaveolens, Asparagus laricinus, Grewia flava, Ziziphus zeyheriana*, and *Ehretia rigida*. Dominant trees: *Vachellia karroo, Senegalia caffra, Celtis africana, Searsia* *leptodictya, Searsia pyroides, Vachellia robusta, Dombeya rotundifolia* var. *rotundifolia*, and *Euclea undulata*. 30 % of the Grassland Biome is considered permanently transformed, of this 23 % is due to agriculture and 2 % to urbanization (Mucina and Rutherford 2006).

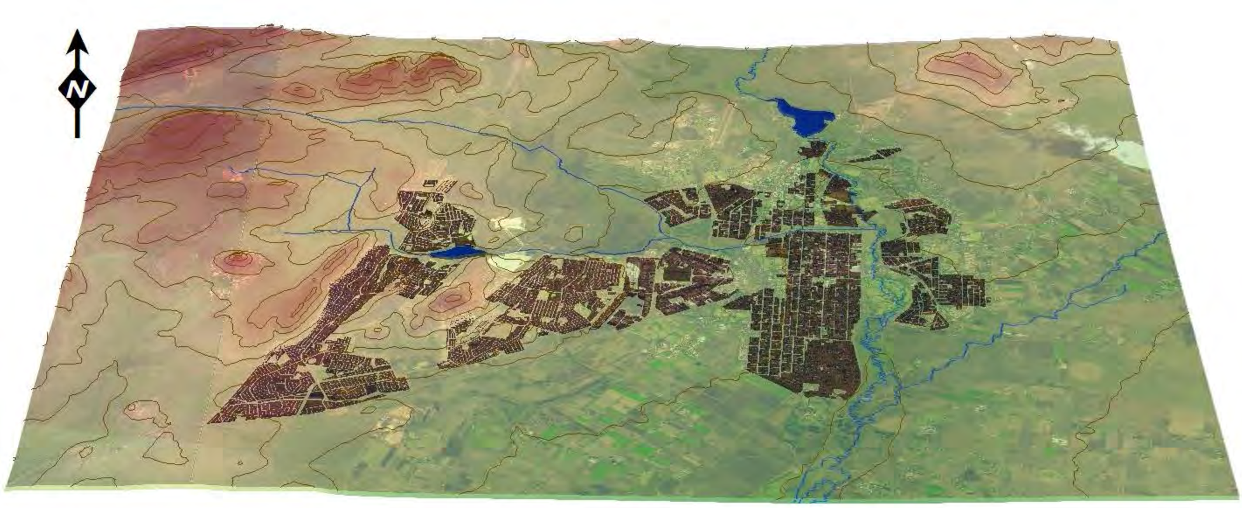

Figure 2: Digital terrain model of the Potchefstroom area indicating the hills and ridges in the western part of the study area. The elevation varies from 1320 to 1520 m.

Figure 3: Examples of three open grassland sites of the Rand Highveld Grassland (top row) and three woody grassland sites representing the Andesite Mountain Bushveld vegetation (bottom row) as found in the study area.

Potchefstroom was established in 1838 as a temporary settlement of Dutch farmers and settlers during the Great Trek out of the British-ruled Cape Colony (Badenhorst 1939). In 1841, it was decided to settle permanently in the area (van den Bergh 1992). Socio-economically, the current spatial organization of residential areas is distinctive with major disparities between the average stand sizes of the townships (non-white residential areas) of Mohadin, Ikageng, Promosa and the traditional white residential areas in the eastern part of Potchefstroom (Figure 4). Segregation of residents based on their specific ethnic groups began in 1877 with the proposal of a separate residential area (called "location") for natives (Coloured and

African people) (Neser 1967). The first "location" was situated at the southern end of the town, with an additional specific demarcated area for people of Indian origin as well. Further segregation took place during the 1950s. The Group Areas Act of 1950 provided for the compulsory zoning of all urban areas into exclusive group areas (Christopher 2001). All residents in the old "location" were to be resettled in newly proclaimed separate townships in the town commonage area along the western border of the urban area. Resettlement of the residents of the township areas was respectively in 1957 (Ikageng), 1969 (Promosa), and 1971 (Mohadin) (Hellberg 1970; Neser 1967) (Figure 1). The advent of democracy in 1994 and the lift of urban restriction laws saw the rapid influx of thousands of South Africans to cities and towns. In Potchefstroom, this resulted in the expansion of the township areas and the development and growth of the Ikageng Extension area (Figure 1). Twenty years after 1994 residential areas still remain largely segregated and a major socio-economic gradient is present from the western to the eastern part of the city (Lubbe et al. 2010).

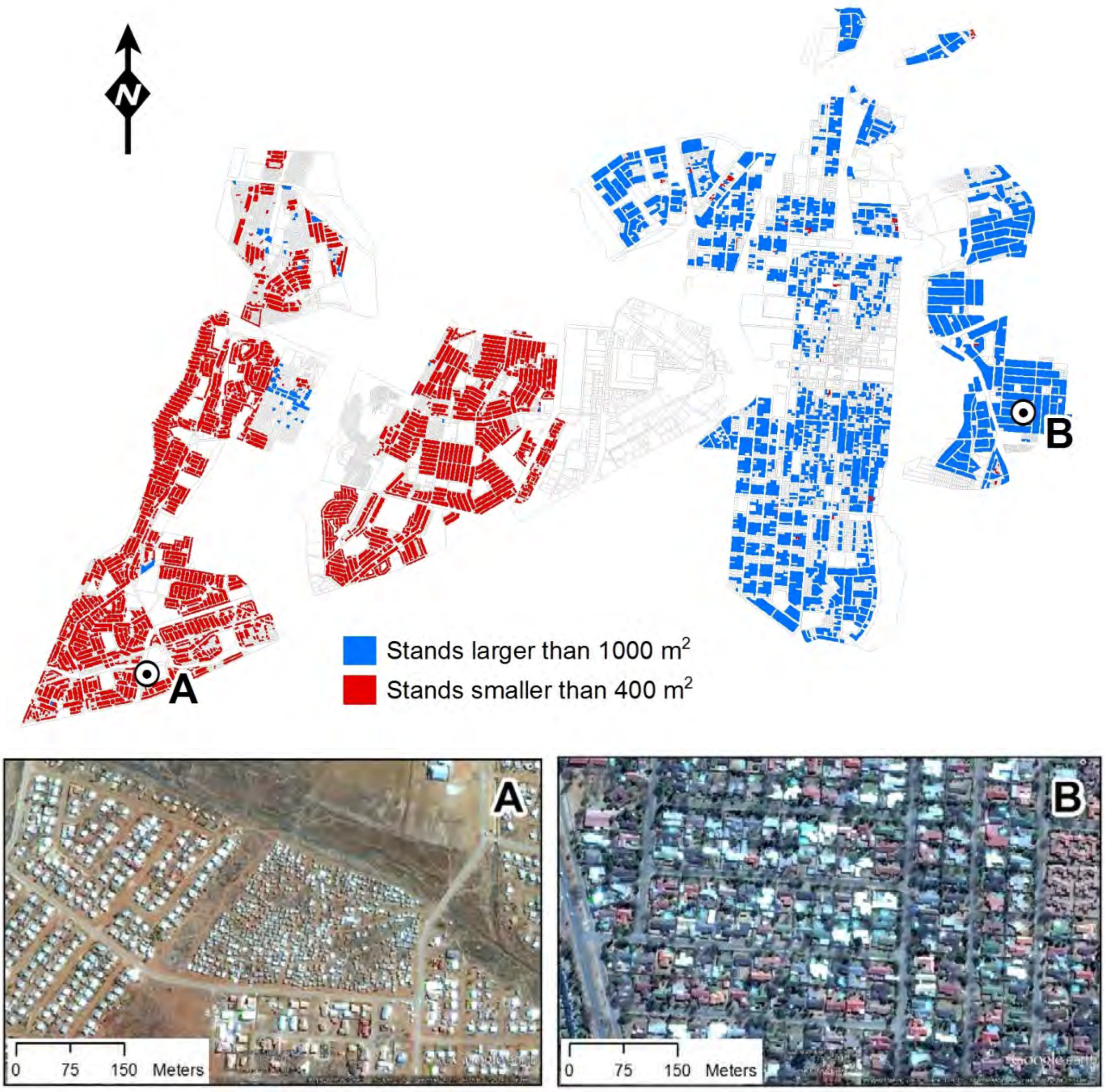

Figure 4: Map of the Potchefstroom residential areas indicating stands smaller than 400 m^2 (grey) and the much larger stands of 1000 m^2 and bigger (black). Shown are satellite images from poor former township residential areas (site A on the map) and those characteristic of the rest of the residential areas (Site B on the map).

Thesis structure and contents

The thesis consists of four papers that will be submitted to the journals *Urban Ecosystems, Landscape Ecology, and Landscape and Urban Planning* and a general conclusion.

The first paper is a comprehensive literature review on the development and research themes of urban ecological research in South Africa. No such review has yet been carried out in South Africa. The paper evaluates previous publications based on the approaches of public participation, management, biodiversity, ecosystem services, resilience, sustainability, physical environment, planning, and human needs. The impact of each publication and approach was calculated using the number of citations per publication and its publication date. This unique quantitative approach was followed to determine which publications and approaches were the most important and dominant through the years. Additionally, the evaluation of the current research allowed the identification of research gaps.

The second paper correlates landscape history with the surveyed vegetation patterns in 1995 and 2012 to determine if there are any legacy effects in the vegetation patterns. Urban landscape measures were quantified for seven time periods from 1938-2010. Generalized linear models were used to determine possible time lags and to identify which measures best predicted the observed vegetation patterns and how these compare between the vegetation patterns of 1995 and 2012.

The third paper focuses on the temporal vegetation dynamics of urban grasslands in Potchefstroom. Surveys carried out in 1995 in natural areas (open grassland and woody vegetation communities), and vacant lots were resampled in 2012 to determine changes in floristic composition and species distribution due to urbanization.

The fourth paper synthesizes all relevant existing research carried out in Potchefstroom. These studies encompass disciplinary research in zoology, botany, and microbiology; including interdisciplinary research incorporating aspects of geography, planning, and social sciences. This is evaluated against municipal management strategies, environmental law and the steep spatially organized socio-economic gradient found in Potchefstroom. Emergent knowledge and the identification of research gaps will allow Potchefstroom to plan for sustainable future solutions and to emerge as a leading role player in the South African urban ecological context.

Lastly, the general conclusion provides a synthesis and discusses the relevance of the knowledge gained in a global context. Future research strategies are discussed to advance urban ecology locally and its contribution to the wider global audience.

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Development and current directions of urban ecological research in South Africa.

M.J. du Toit and S.S. Cilliers

Abstract

The science of urban ecology has grown into a globally significant field that seeks to understand the complex relationships between human settlements and their ecological contexts in an attempt to ensure sustainable futures. Several reviews have been written on its development and scientific advancements in the field. Nonetheless, there exists a large disparity in the amount of literature from the global South in comparison to that of the North. South Africa is one of the few countries in the global South actively engaged in urban ecological studies. Contributions started in the early 1960s and in recent times some researchers have produced world-renowned studies. However, no comprehensive overview of South African urban ecological literature exists. Therefore, the aim of this paper is to discuss the early development, research themes and the future of urban ecology in South Africa. We reviewed 314 publications and categorized them into the following themes: physical environment, biodiversity, management, conservation, planning, human needs, sustainability, public participation, ecosystem services, and resilience. This synthesis and the subsequent identification of the gaps in our understanding and research themes will allow a purposeful and informed advancement of the science of urban ecology in South Africa and the contribution thereof towards advancing urban ecology globally.

Keywords: Urban ecology, public participation, human needs, ecosystem services, conservation, management, planning, biodiversity, sustainability, resilience, physical environment, South Africa.

Introduction

Cities are the ultimate human creation. Nothing is more convincing than the fact that more than half the world's population are now urbanites (United Nations 2014). It is therefore not surprising that the discipline of urban ecology has shifted from an young emerging science in the 1970s (McDonnell 2011) to an essential science in our contemporary urban world (Pacione 2005). Moreover, urban ecological research has moved beyond disciplinary boundaries and is "*evolving and emerging into a truly inter- and transdisciplinary science*" (McDonnell 2011). Accordingly, Cilliers and Siebert (2012) adapted the urban ecology definition of Marzluff et al. (2008b) to an "*emerging* interdisciplinary and transdisciplinary *field that aims to understand how humans and ecological processes can coexist in human-dominated systems and help societies with their efforts to become more sustainable*."

A number of reviews have been published on urban ecological research (e.g. Alberti 2005; Chace and Walsh 2006; McKinney 2008; Pickett et al. 2008; Pickett et al. 2011; Magle et al. 2012; Wu 2014). However, most of the studies cited were carried out in America and Europe. Therefore, McDonnell et al. (2009) call for more globally comparative studies to enhance ecological understanding of urban areas and aid in determining generalizable principles. Knowledge of South African studies, as part of the global South, can contribute to this global urban ecological knowledge. Moreover, floristically South Africa contains three global biodiversity hotspots (Conservation International 2014). The Cape Floristic Region, the Maputaland-Pondoland-Albany region, and the Succulent Karoo are located in an approximately 120 km wide strip along the entire South African coastline and include several urban areas (Fig. 1). Urban ecology is gaining momentum in South Africa, and this paper serves as a timely review of the development and current directions of urban ecological research in South Africa. It builds upon and greatly expands on the first review carried out by Cilliers and Siebert (2012) as part of a special issue on the ecology of Cape Town. The aim of this paper is to discuss the early development, research themes and the future of urban ecology in South Africa. We review globally recognized themes in urban ecology namely: public participation, human needs, ecosystem services, physical environment, conservation, planning, management, biodiversity, sustainability, and resilience to greatly enhance local efforts and to meaningfully contribute to international discourse.

South African urban development

South Africa probably has some of the most contentious urban history in the world. Literature is replete with views and opinions on the subject, and the term *Apartheid* and its implications are known throughout the world. The first incentive for population concentration in urban settlements in South Africa was with the first Europeans arriving in 1652 in the Cape (Van der Merwe and Nel 1981). The second and first real stimulus for urban development was the mineral revolution of the 19th century—the discovery of diamonds in 1861 and gold in 1886 (Holzner 1970; Van der Merwe and Nel 1981; Feinstein 2005). Before these discoveries, only 18 urban areas boasted a population of over 1000 residents (Holzner 1970). Because mining and the related subsequent harbour activities were the only real incentive for urban growth most of it took place in the few existing centres at that time and by the 1970s, 75% of the urban population lived in Gauteng (then known as the Southern Transvaal conurbation), Cape Town, Durban, Port Elizabeth and East London (Holzner 1970). The effects and influences of the colonial and succeeding Apartheid era and the consequences of the infamous racial segregation and land ownership acts on urban development and human geography in South Africa are well documented (e.g. Stent 1948; Holzner 1970; Davies 1981; Christopher 1983; Christopher 1987; Murray 1987; Lemon 1991; Crankshaw 1993; Maylam 1995; Parnell and Mabin 1995). Thereafter, the political climate and settlement landscape changed drastically after democracy in 1994. This is reflected in several post-Apartheid urban studies describing the subsequent development and challenges now faced in the *new South Africa* (e.g. Parnell 1997; Seidman 1999; Christopher 2001; Cox et al. 2004; Todes et al. 2010; Nel 2011).

Today, South Africa has evolved into a complex web of political, social, economic and environmental realities where wide ranging attitudes apply: South Africa is faced with immense socio-economic issues (du Plessis et al. 2003), many disregard environmental issues (Whyte 1995; Le Maitre et al. 2007), and struggling municipalities cannot cope with urbanization rates which increase pressure on limited resources in strained social contexts (Carden and Armitage 2013). Environmentally, the situation has been elegantly summed up by Crane (2006) stating that "*South Africa is unique in two quite distinct ways. First, it is a country with massive biodiversity. The third most biologically diverse country in the world [...] Second, South Africa has an extreme history of land dispossession based on racial discrimination, which has produced a highly unequal pattern of land ownership and widespread rural poverty*." Out of the discrimination of the past and the problems facing citizens today, this is the South African context in which urban ecological research need to strive to become the panacea of sustainable and responsible survival.

Early development of urban ecological themes in South Africa

Early botanical studies were concisely described by Percy Phillips in his presidential address to the South African Association for the Advancement of Science in 1930 entitled *A brief historical sketch of the* *development of botanical science in South Africa and the contribution of South Africa to Botany* (Phillips 1930). Herein he points out that the first reference to a botanical publication printed and published in South Africa (and incidentally of a pre-urban ecological nature) is a list of plants found in the Uitenhage district (Ecklon 1830). Later on the *Memoirs of the Botanical Survey of South Africa* series was published, and included research linked to settlement areas. However, the surveys were largely conducted in the natural areas surrounding the settlements, with rare specific mention of the plants found in the settlements themselves. The very first issue described the phanerogamic (seed-bearing) plants of the greater Uitenhage and Port Elizabeth area (Schönland 1919), additional issues include, amongst others, the Riversdale area (Muir 1929), the Albany and Bathurst area (Dyer 1937), the area surrounding George, Knysna, Humansdorp, and Uniondale (Fourcade 1941), the Potchefstroom area (Louw 1951), and the Bloemfontein and Brandfort district (Mostert 1958). Pappe wrote the first publications on economic botany in 1840-60, including his *Florae capensis medicae prodromus, or, an enumeration of South African indigenous plants used as remedies by the colonists of the Cape of Good Hope* (Pappe 1850).

The first noteworthy research of an urban ecological nature is that of birds in human settlement areas. Haagner (1902) published bird species lists observed in Johannesburg and Modderfontein. The Journal of the South African Ornithologists' Union published from 1905-1916 contains an article in its first issue by Shortridge (1905) on bird observations and collected specimens in the town of Hanover. Subsequent issues include, amongst others, studies in Modderfontein by Haagner (1905), in Wolmaransstad by Roberts (1906), in Irene by Taylor (1906), and in the King William's Town area by Pym (1909). The ornithological journal, Ostrich, first issued in 1930 also published research in settlement areas, amongst others, garden birds in Johannesburg (Knox-Davies 1931), birds observed in Graaff-Reinet (Taylor 1937), Richards Bay (Gilges 1945), and Grahamstown (Beven 1945). Lastly, The South African Avifauna Series journal of the Percy FitzPatrick Institute of African Ornithology (Niven Library online catalogue: http://nivenlib.pfp.uct.ac.za/amlibweb/webquery.dll?v20=1&v22=1M), published from 1961-1972, dedicate almost half of the 92 issues to settlements and/or settlement districts e.g. the birds of the East London Area (Courtenay-Latimer 1964), a list of the birds of Potchefstroom (Brandt and Malherbe 1967), and a list of the birds of Durban (Lawson 1971).

Descriptive urban ecological studies began to appear in the latter half of the 20th century. Urban climate studies were carried out in Pretoria (Louw and Meyer 1965; Gogh 1979; Morkel 1980), Pietermaritzburg (Tyson 1968), and Johannesburg (Goldreich 1970; Goldreich 1971; Tyson and Von Gogh 1976; Goldreich 1979; Goldreich 1992). Other urban studies include urban planning research (Poynton and Roberts 1985; Wall 1992; Wisner and Luce 1995); medicinal plant usage in urban areas (Dauskardt 1990a; Williams et al. 1997); urban agriculture (Rogerson 1993; May and Rogerson 1995); urban biodiversity such as invertebrates (Wood and Samways 1991; Steytler and Samways 1995) and vegetation (Roberts 1993; Berry et al. 1994; Cilliers et al. 1998; Cilliers and Bredenkamp 1998); and urban management and governance (Wisner 1995; McDonald 1997; Armitage and Rooseboom 1999).

Methods

A comprehensive literature survey was conducted to find environment related studies on the interaction between humans and nature carried out in human settlements in South Africa. The focus was on urban areas, but studies were also included that were carried out in small towns and villages where relevant. The reasoning behind the inclusion of villages in rural areas is firstly due to the viewpoint of McHale et al.

(2013) that rural is the new urban in discussing urbanization in the global South. Secondly, some specifically stated urban ecological studies in South Africa have been carried out in villages (e.g. van Rooyen 2009; Cilliers et al. 2011a). Furthermore, almost every town and city in South Africa have associated with them large residential areas of poor inhabitants where densely packed houses have been haphazardly constructed with corrugated iron and any other type of building materials available, called informal settlements, displaying many typical rural characteristics. Moreover, some rural areas have high population densities and active informal economic production (McHale et al. 2013). The selected publications were categorized according to the following themes adapted from Niemelä (2011); Pickett et al. (2011) and Cilliers and Siebert (2012) to represent the dominant trends in South African literature, namely: physical environment (air, soil, pollution, water, climate change, disasters); biodiversity; management; conservation; planning; human needs (medicinal plants, urban agriculture, trees and fuel wood); sustainability; public participation (civic science; civic ecology; environmental justice and political ecology; and use of surveys, interviews and questionnaires); ecosystem services; and resilience (Table 1). Each publication was categorized according to the main themes discussed therein. However, in the case of the physical environment theme, publications were only included if the researcher did actual measurements such as soil analyses. Publications included in the biodiversity theme were those either studying a species or those which included species lists. Moreover, publications were not restricted to one theme, it could represent several themes, in other words, a publication on birds discussing management recommendations would have been categorized as biodiversity and management.

Literature surveys were conducted using Google Scholar and EBSCO's OneSearch search platform of the North-West University library (http://www.nwu.ac.za/library/onesearch.html). OneSearch accesses 90 international databases to which the NWU Library subscribes—listed on the above-mentioned website are some of the databases included in every search. Keywords used were 'urban' in conjunction with 'agriculture, animals, arthropods, biodiversity, birds, civic science, climate, climate change, ecology, ecosystem services, environment, environmental justice, mammals, medicinal, planning, political ecology, resilience, soil, sustainability, vegetation, water, management'. Additionally, the reference lists of the surveyed articles were also used to find more articles. Searches were limited to dissertations/theses, books/book chapters and published peer reviewed papers. We ultimately selected and reviewed 314 publications (Supplementary Information Table 1 lists all the publications and their specific theme categorization). To objectively and accurately determine the significance and relevance of the themes and specific articles we used Google Scholar citations (http://scholar.google.co.za/) to determine the relative international contribution of each article. The impact of each publication was calculated by dividing the number of citations by the year in which it was published. For articles with an online first or similar publication date, the date used was the one in which it was included in a specific journal issue. We used the Google Scholar citations for the 314 publications as listed on the 27th of August 2014. The total impact per year was calculated as the sum of the impact of all publications published in a specific year.

Table 1 Research themes terminology and abbreviations used in tables and figures.

Biodiversity (B)		**Physical environment (PE)**	
A	Amphibians	A	Air
AL	Algae	C	Climate
BC	Bacteria	CG	Climate change
BI	Birds	D	Disasters
F	Fish	P	Pollution
FG	Fungi	S	Soil
I	Invertebrates	W	Water
M	Mammals	WB	Water bodies
R	Reptiles		
V	Vegetation	**Planning (PL)**	
Conservation (C)		**Public participation (PP)**	
		CE	Civic ecology
Ecosystem services (ES)		CJ	Conservation justice
		CS	Civic science
Human needs (HN)		EJ	Environmental justice
A	Urban agriculture	PE	Political ecology
M	Medicinal plants	SQI	surveys/questionnaires/ interviews
TF	Trees and fire/fuel wood		
		Resilience (R)	
Management (M)			
MC	Municipal commonage	**Sustainability (S)**	

Urban ecological research in South Africa

The research of the 314 evaluated publications was carried out in 141 settlements (ranging from metropolitan urban areas to rural villages), two district municipalities, 27 local municipalities and 21 magisterial districts. Sixty-eight percent of the studies were carried out in one settlement or urban area only. Figure 1 shows a map of the location of the studied settlements and municipalities in South Africa. The urban areas wherein most research was carried out are Cape Town (62), Durban (50), Johannesburg (38), Potchefstroom (28), Pretoria (26) and Grahamstown (12). Included in these numbers are the studies carried out in the corresponding entire local municipal areas as well. Figure 2 indicates the provincial distribution of the studies with the Western Cape representing 25%, Kwazulu-Natal and Gauteng both 21%, North-West 14%, Eastern Cape 13%, and the rest collectively 8% of the studies. Of the evaluated studies, 75% were authored by local scholars, 17% were local and international author co-operations, with 8% authored by international scholars only. Overall, the impact of urban ecological literature began to increase from 2000 onwards (Figure 3). Furthermore, since 2006 the total impact of the articles exceeds 50 citations per year (Figure 3). The total number of citations from 1965-1999 (34 years) equals 1093, representing 46 articles, and from 2000-2014 (14 years) is 4549, from 268 articles.

A list was compiled of the top ten articles with the highest citations (Table 2) and the top ten articles with the highest impact (Table 3). The South African article with the highest number of citations is the study carried out by Shackleton and Shackleton (2004) on rural livelihoods and their reliance on non-timber forest products. Despite the overall low influence of the human needs theme (Table 4 and Figure 9), the second highest citations article is also part of this theme. This is the article by Dold and Cocks (2002) on the medicinal plant trade. By comparison, the two highest impact articles are a study on urban resilience (Ernstson et al. 2010) and a recent article on the importance of social values on ecosystem service outcomes (Ernstson 2013). In 2011, there was a marked decline in total impact and the highest impact of an article (Fig. 3). A likely explanation could be found by studying Table 4 and Figures 4-13. The number of publications published in 2011 was 23, compared with 28 in 2010 and 35 in 2012. In Table 4 the highest impact themes for 2011 were public participation, management, conservation and biodiversity. No influential articles were published that year on the globally popular topics of ecosystem services, climate change, sustainability and resilience.

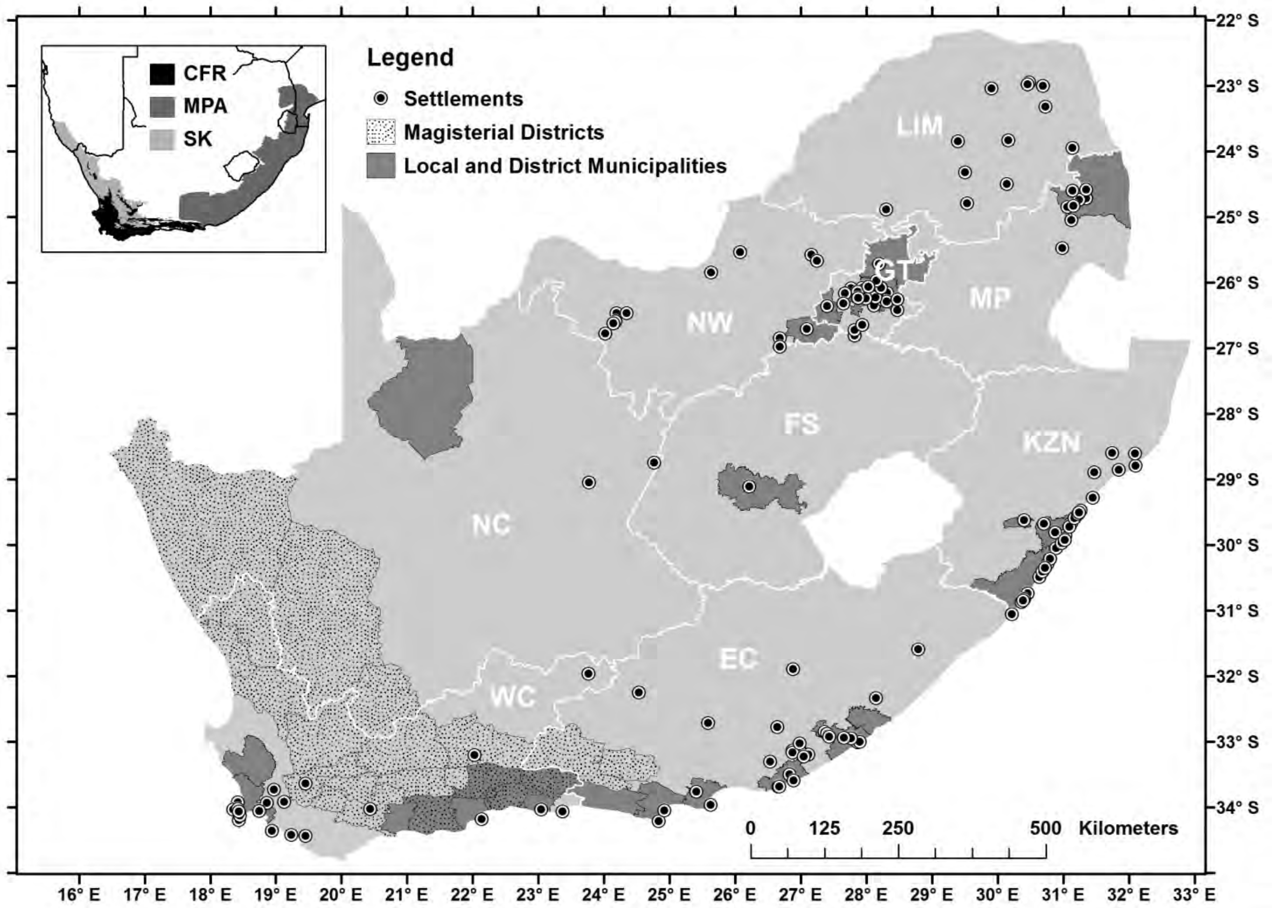

Fig. 1 Map showing the distribution of the settlements, local and district municipalities and the magisterial districts in which urban ecological studies have been conducted in South Africa. South Africa is divided into nine provinces: Western Cape (WC), Eastern Cape (EC), Northern Cape (NC), Free State (FS), North-West (NW), Kwazulu-Natal (KZN), Gauteng (GT), Mpumalanga (MP), and Limpopo (LIM). The inset map shows the location of the three global biodiversity hotspots in South Africa, namely the Cape Floristic Region (CFR), the Maputaland-Pondoland-Albany (MPA) region, and the Succulent Karoo (SK).

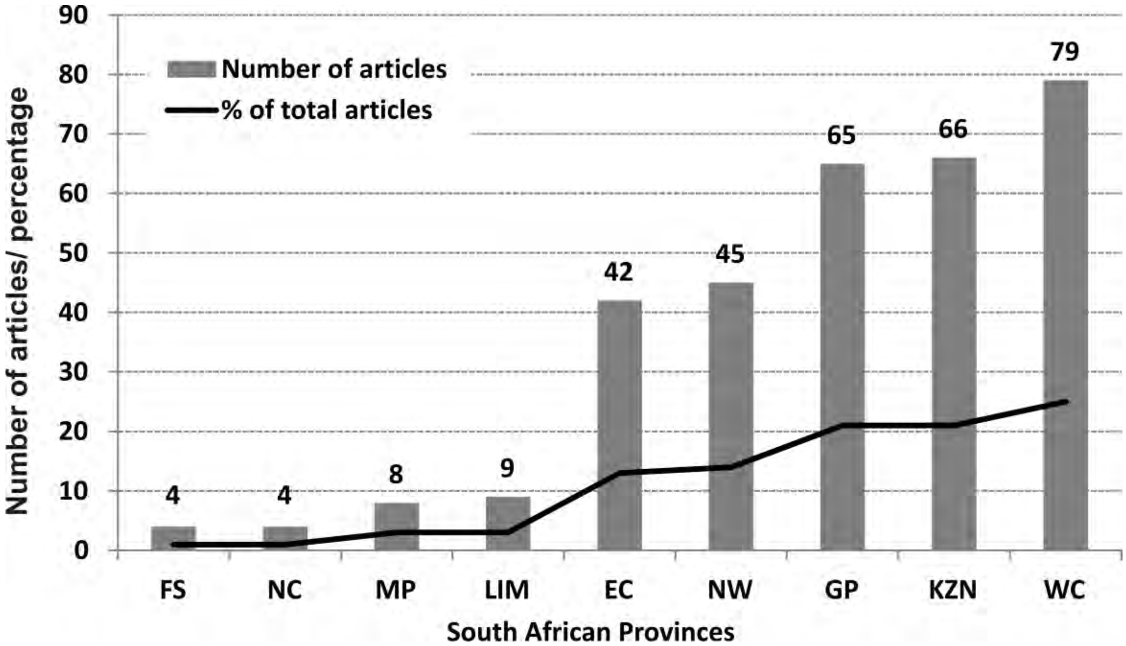

Fig. 2 Graph of the number and percentage of studies carried out per provincial area in South Africa. (Abbreviations of the province names as indicated in Figure 1).

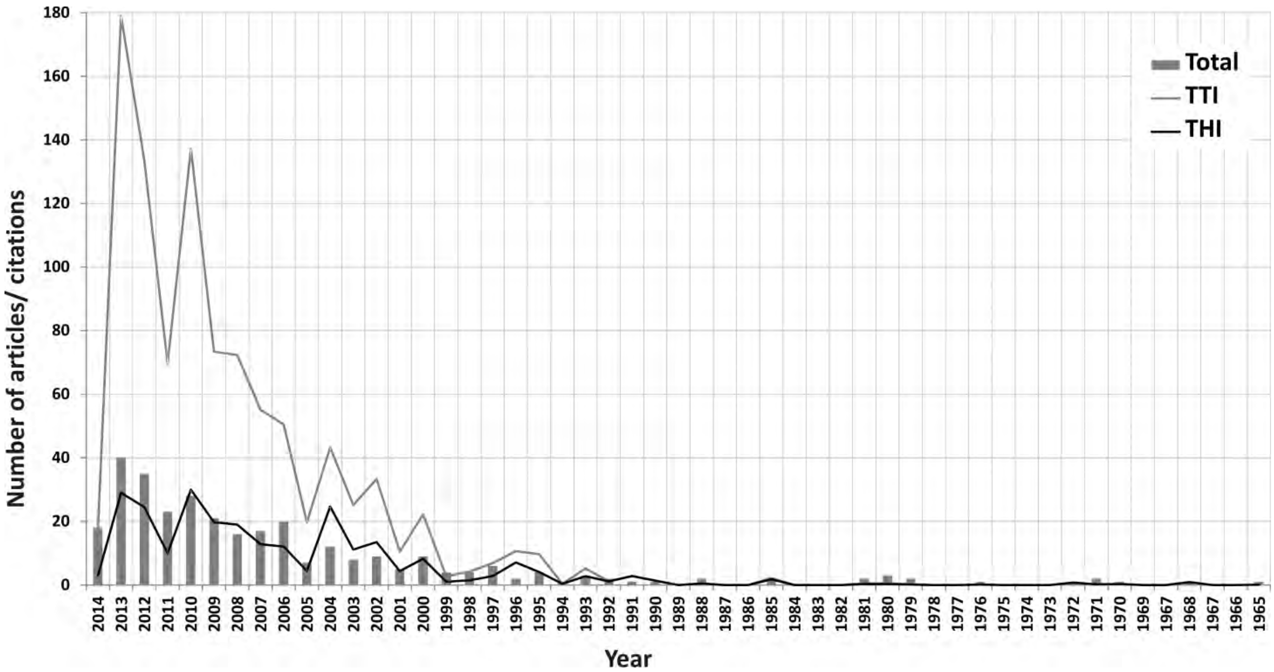

Fig. 3 The total number of articles published per year, indicating the total impact of all articles per year (TTI) and the highest impact article (THI) for each year.

Table 2 Top ten articles with the highest citations (Google Scholar 27 Aug 2014). Abbreviations for the themes as in Table 1.

Reference	Title	CIT	IMP	Themes
Shackleton and Shackleton (2004)	The importance of non-timber forest products in rural livelihood security and as safety nets: a review of evidence from South Africa	247	24.70	PP(SQI); HN(TF)(M)(A); B(V); S
Dold and Cocks (2002)	The trade in medicinal plants in the Eastern Cape Province, South Africa	162	13.50	PP(SQI); HN(M); C; B(V); S
Samways and Steytler (1996)	Dragonfly (Odonata) distribution patterns in urban and forest landscapes, and recommendations for riparian management	128	7.11	M; C; PE(WB); B(I)(V)
Naicker et al. (2003)	Acid mine drainage arising from gold mining activity in Johannesburg, South Africa and environs	123	11.18	PE(WP)(SP)
Ernstson et al. (2010)	Urban Transitions: On Urban Resilience and Human-Dominated Ecosystems	120	30.00	PP(CE); ES; M; C; PE(W)(CG); PL; B; S; R
Williams et al. (2000)	Unraveling the Commercial Market for Medicinal Plants and Plant Parts on the Witwatersrand, South Africa	116	8.29	PP(SQI); HN(M); B(V)
Roberts (2008)	Thinking globally, acting locally – institutionalizing climate change at the local government level in Durban, South Africa	114	19.00	M; PE(CG); PL; B; S
Watson (2009)	'The planned city sweeps the poor away. . .': Urban planning and 21st century urbanisation	99	19.80	M; PL; S
Alston and Richardson (2006)	The roles of habitat features, disturbance, and distance from putative source populations in structuring alien plant invasions at the urban/wildland interface on the Cape Peninsula, South Africa	97	12.13	M; C; PE(S); B(V)
Mukheibir and Ziervogel (2007)	Developing a Municipal Adaptation Plan (MAP) for climate change: the city of Cape Town	90	12.86	M; PE(D)(W)(CG); PL; S; R

Table 3 Top ten articles with the highest impact (Google Scholar 27 Aug 2014 citations/publication age).

Reference	Title	CIT	IMP	Themes
Ernstson et al. (2010)	Urban Transitions: On Urban Resilience and Human-Dominated Ecosystems	120	30.00	PP(CE); ES; M; C; PE(W)(CG); PL; B; S; R
Ernstson (2013)	The social production of ecosystem services: A framework for studying environmental justice and ecological complexity in urbanized landscapes	29	29.00	PP(EJ); ES; M; PL; B; R
Shackleton and Shackleton (2004)	The importance of non-timber forest products in rural livelihood security and as safety nets: a review of evidence from South Africa	247	24.70	PP(SQI); HN(TF)(M)(A); B(V); S
Carmin et al. (2012)	Urban Climate Adaptation in the Global South: Planning in an Emerging Policy Domain	49	24.50	PP(SQI); M; PE(CG); PL; S; R
Watson (2009)	'The planned city sweeps the poor away. . .': Urban planning and 21st century urbanisation	99	19.80	M; PL; S
Roberts (2008)	Thinking globally, acting locally – institutionalizing climate change at the local government level in Durban, South Africa	114	19.00	M; PE(CG); PL; B; S
Schäffler and Swilling (2013)	Valuing green infrastructure in an urban environment under pressure — The Johannesburg case	18	18.00	PP(SQI); ES; M; PL; B(V); S; R
Ernstson and Sörlin (2013)	Ecosystem Services as Technology of Globalization: On Articulating Values in Urban Nature	16	16.00	PP(SQI); ES; M; C; S; R
Roberts et al. (2012)	Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face	29	14.50	M; C; PE(CG); PL; B(V); S; R
Roberts (2010)	Prioritizing climate change adaptation and local level resilience in Durban, South Africa	55	13.75	M; PE(D)(CG); PL; B; S; R

Table 4 Percentage contribution of each theme to the total impact per year from 1990 - 2014. The number of publications is shown in brackets. Grey shaded cells indicate contributions of 50% and more. Listed are the percentage physical environment articles of the total impact (%PETI), the contribution of the climate change articles only (%PE(CG)TI), biodiversity (%BTI), management (%MTI), conservation (%CTI), planning (%PLTI), human needs (%HNTI), sustainability (%STI), public participation (%PPTI), ecosystem services (%ESTI), , and resilience (%RTI).

Date	%PETI	%PE(CG)TI	%BTI	%MTI	%CTI	%PLTI	%HNTI	%STI	%PPTI	%ESTI	%RTI
2014 (18)	33 (8)	17 (4)	44 (11)	50 (9)	22 (7)	61 (7)	33 (5)	44 (8)	67 (12)	22 (3)	17 (3)
2013 (40)	42 (23)	30 (10)	45 (18)	80 (22)	31 (14)	59 (15)	9 (5)	54 (17)	65 (18)	50 (8)	56 (8)
2012 (35)	50 (16)	37 (7)	55 (20)	82 (24)	57 (20)	49 (12)	13 (6)	67 (18)	51 (15)	20 (7)	39 (6)
2011 (23)	20 (6)	4 (2)	63 (13)	53 (11)	53 (12)	38 (7)	26 (8)	37 (10)	53 (14)	7 (2)	4 (2)
2010 (28)	63 (14)	52 (6)	69 (17)	59 (12)	38 (9)	58 (11)	15 (6)	54 (11)	67 (17)	33 (3)	32 (2)
2009 (21)	44 (10)		43 (13)	61 (10)	10 (5)	39 (5)	15 (6)	49 (9)	19 (6)	3 (1)	
2008 (16)	44 (6)	35 (2)	82 (12)	48 (7)	27 (8)	34 (3)	28 (4)	55 (6)	32 (7)		
2007 (17)	54 (11)	37 (2)	22 (7)	66 (10)	3 (3)	27 (4)	27 (5)	60 (8)	70 (11)	6 (3)	28 (2)
2006 (20)	53 (11)	-1	47 (10)	64 (10)	37 (4)	25 (5)	22 (5)	33 (6)	39 (10)	-1	
2005 (7)	51 (3)		21 (1)	47 (4)	24 (2)	26 (3)	43 (2)	47 (4)	66 (4)	3 (1)	
2004 (12)	20 (5)	3 (1)	66 (4)	37 (8)	28 (7)	23 (6)	60 (2)	91 (9)	82 (6)		3 (1)
2003 (8)	55 (2)	11 (1)	30 (3)	26 (5)	29 (1)	15 (3)	53 (4)	26 (4)	46 (6)		
2002 (9)	28 (5)	5 (1)	76 (5)	11 (3)	55 (4)	5 (1)	62 (2)	52 (3)	69 (4)		
2001 (5)	23 (2)		10 (1)	48 (3)	35 (2)	25 (1)	52 (2)	39 (2)	86 (4)		
2000 (9)	51 (5)		66 (5)	25 (3)	4 (1)	4 (1)	46 (3)	4 (1)	49 (4)		
1999 (4)	100 (4)		62 (3)	69 (2)	31 (1)		31 (1)				
1998 (4)	34 (2)		34 (2)	35 (1)	53 (2)	31 (1)	31 (1)	66 (2)	66 (2)		
1997 (6)	7 (2)		82 (4)	33 (2)	85 (5)		26 (2)	11 (1)	33 (3)		
1996 (2)	67 (1)		67 (1)	67 (1)	67 (1)		33 (1)	33 (1)	33 (1)		
1995 (4)	58 (3)		32 (1)	100 (4)	32 (1)	65 (2)	42 (1)	65 (2)	68 (3)		
1994 (1)			100 (1)		100 (1)		100 (1)				
1993 (3)	7 (1)		7 (1)	39 (1)		39 (1)	93 (2)	39 (1)			
1992 (2)	100 (1)				-1	-1					
1991 (1)			100 (1)	100 (1)	100 (1)						
1990 (1)							100 (1)				
TY>50	**11**	**1**	**12**	**12**	**8**	**4**	**7**	**9**	**12**	**1**	**1**
% of the 314 publications	**50%**	**12%**	**50%**	**49%**	**36%**	**29%**	**24%**	**39%**	**47%**	**9%**	**8%**

Research themes

Physical environment

Research on the physical environment plays a dominant and consistent part of South African urban ecological literature (Table 4, Fig. 4). Figure 4 shows the physical environment research in comparison with the total contributions per year as well as showing the impact and highest impact articles per year and the specific contribution of the climate change articles. Contributions from this theme steadily increased from 2006 onwards (Fig. 4). For 11 of the 25 years listed in Table 4, physical environmental themes contributed to more than 50% of the total impact per year. Of the 314 evaluated publications, 157 (50%) included research on the physical environment. It is also the earliest descriptive urban ecological research in South Africa. The main themes are climate and specifically climate change; soil; water and water bodies; pollution of air, soil and water; and environmental disasters. In the period of 1965 - 1992 a series of urban climate studies were carried out, mainly on the urban heat island effect, in the cities of Pretoria (e.g. Louw and

Meyer 1965; Gogh 1979), Johannesburg (e.g. Goldreich 1970; Tyson et al. 1972; Goldreich 1992), Pietermaritzburg (Tyson 1968; Tyson et al. 1972) and Durban (Tyson et al. 1972). The few other climate studies since then, excluding those dealing with climate change, include an urban heat island study (Goldreich 2006) and the study of Hoffman and O'Riain (2011) wherein they inter alia measured daily ambient air temperatures at chacma baboon habitats.

There is a paucity of research on urban soils in South Africa. Research on urban soils has been mostly in the form of soil analyses taken as part of habitat factors and environmental variables in plant communities (Cilliers and Bredenkamp 1998; Grobler et al. 2006; Daemane et al. 2010; Meek et al. 2013) and other vegetation studies (Alston and Richardson 2006; du Toit 2009). The only literature found specifically focusing on soil (excluding pollution which will be discussed separately) is on soil biodiversity (Jansen van Rensburg 2010), fungal pathogens in soil (Van der Walt et al. 2007), soil erosion (Smith et al. 2013), landscape functionality (van der Walt et al. 2015) and two urban agriculture based studies of soil compaction (Materechera 2009) and soil salinity (Materechera 2011). Within water research, there is a differentiation between water bodies and other water related topics (excluding pollution). By far the most research in and around urban water bodies has been carried out on rivers, in all, 19 of the evaluated studies (e.g. Samways and Steytler 1996; Grobicki 2001; Fatoki et al. 2002; Mgquba and Vogel 2004; Meek et al. 2010; Wyma 2012; Jackson et al. 2013). The other water bodies included wetlands (e.g. Cilliers et al. 1998; Lannas and Turpie 2009; Katz et al. 2014), coastlines and estuaries (e.g. Becker et al. 2013a; Mead et al. 2013; McQuaid and Griffiths 2014), dams (e.g. Marchand et al. 2009; Pieterse et al. 2010; Davies et al. 2013), and lakes (Venter 1971; Steytler and Samways 1995; García-Rodríguez et al. 2007; Burger 2008; Olowoyo et al. 2012). The rest of the water literature was focused on urban water management, supply and sustainability (e.g. Morrison et al. 2001; Saayman and Adams 2002; Riemann et al. 2012; Carden and Armitage 2013).

Human settlements and environmental pollution are inseparable. Fifty-one studies report on pollution of air, soil and water sources. By far the city with the most publications on pollution is Durban, almost all of it related to air pollution. In this regard Durban is infamous for its fight for environmental justice and civic society actions related to air pollution problems (e.g. Scott et al. 2002; Barnett and Scott 2007b; Scott and Barnett 2009; Aylett 2010a). Other Durban located studies include soil pollution due to a landfill site and its related problems (Leonard 2011; Leonard 2012) and a mammal study on the effects of polluted water usage on bats (Naidoo et al. 2013). Further pollution studies include air pollution in Cape Town (Wilson et al. 2009; Nzotungicimpaye et al. 2014) and the impact and management of urban litter in storm water drainage systems (e.g. Armitage and Rooseboom 1999; Armitage 2007); soil and water pollution due to mining activities (Rösner and Van Schalkwyk 2000; Naicker et al. 2003; Van Eeden 2006; Van Eeden 2008); soil, water and air pollution from trace metals via vehicle emissions, industrial discharges, etc. (e.g. Odiyo et al. 2005; Okonkwo and Mothiba 2005; Okonkwo et al. 2006; García-Rodríguez et al. 2007; Olowoyo et al. 2010; Olowoyo and van Heerden 2012); and faecal water pollution (Pantshwa 2006).

"*The greenhouse effect is a hot topic*" (Tol 1995). The vast literature focusing on climate change began in the 1990s globally. The first article addressing climate change in urban South Africa is that of Roberts and Diederichs (2002) in Durban. Since then the two articles in 2007 (Holgate 2007; Mukheibir and Ziervogel 2007) and two in 2008 (Roberts 2008; Ziervogel and Taylor 2008) respectively represented 37% and 35% (Table 4) of the total impact for articles published in those years. Later on in 2010 an impressive 52% (represented by six articles) of the total impact was dedicated to climate change research (Table 4). As a result of this research carried out in Durban, the city has stood out as a world leader in climate change adaptation research. Even though only 12% of the 314 articles evaluated discussed climate change, three of the articles in the top ten highest citations in South Africa (Table 2) are research on climate change in Durban (Roberts 2008) and Cape Town (Mukheibir and Ziervogel 2007; Ernstson et al. 2010). Moreover, five of the top ten highest impact articles in South Africa (Table 3) are on climate change, four in Durban (Roberts 2008; Roberts 2010; Carmin et al. 2012; Roberts et al. 2012) and one in Cape Town (Ernstson et al. 2010). Studies related to climate change consisted of the research carried out on mitigation and management of current and expected environmental disasters (e.g. Mgquba and Vogel 2004; Fatti and Vogel 2011; Faling et al. 2012; Friedrich and Kretzinger 2012; Mather and Stretch 2012; Fatti and Patel 2013). Of the other studies documenting environmental disasters, two were mining related (Van Eeden 2006; Van Eeden 2008) and two discussed the environmental risks in the densely populated township of Alexandra in Johannesburg (Wisner 1995; Wisner and Luce 1995).

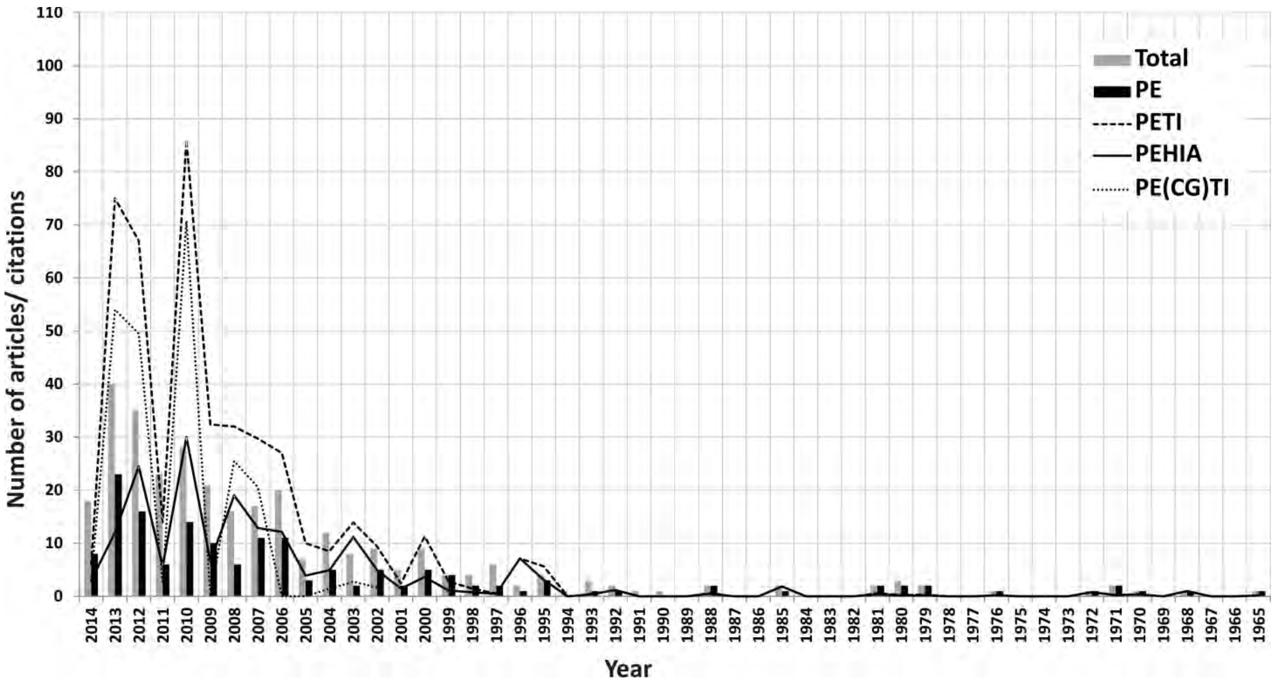

Fig. 4 The number of physical environment articles published per year (black bars), indicating the total impact of the articles per year (PETI) and the highest impact article for each year (PEHIA). Also shown are grey bars representing the total number of all articles per year and the specific contribution of climate change articles to the total impact (PE(CG)TI).

Biodiversity

Traditionally, biodiversity remains one of the main aims of urban ecological studies. It is also one of the earliest themes in South Africa (Fig. 5). Despite the long record of descriptive biodiversity research, the number of articles per year consecutively increased substantially from 2006 onwards (Fig. 5). Half (50%) of all the evaluated articles focused on biodiversity, which were divided into vegetation (69%), birds (16%), invertebrates (12%), mammals (12%), fish (7%), reptiles (4%), amphibians (4%), fungi (3%), algae (2%), and bacteria (1%). Nineteen percent of the articles were multiple group combinations. Excluded in the discussion of vegetation themes here are urban agriculture, medicinal plants, conservation, ecosystem services and management studies as they are discussed separately. The earliest urban vegetation studies found were plant community studies in Richard's Bay (Venter 1971) and Isipingo Beach (Ward 1980). The classification and description of plant communities were common in early urban vegetation research and remain a prominent theme in South Africa (e.g. Cilliers et al. 1998; Cilliers and Bredenkamp 1998; Grobler et al. 2006; Burger 2008; Daemane et al. 2012; Dingaan and du Preez 2013). Vegetation composition and diversity research were carried out in urban domestic gardens (Davoren 2009; Lubbe et al. 2010; Molebatsi et al. 2010; Lubbe et al. 2011; Molebatsi et al. 2013), along urban-rural gradients (du Toit 2009), the response of vegetation to anthropogenic effects (Cilliers et al. 2008; Meek et al. 2010; Lucrezi et al. 2014), and using Landscape Function Analysis methods (van der Walt et al. 2015). Lastly, a few urban forestry studies were also carried out (e.g. Shackleton 2006; Stoffberg et al. 2008; Kuruneri-Chitepo and Shackleton 2011; De Lacy and Shackleton 2014).

Urban bird research was carried out on diversity (Smith 2004; Whittington et al. 2006; van Rooyen 2009), homogenization (van Rensburg et al. 2009; Dures and Cumming 2010), along gradients (van Rensburg et al. 2009), persistence in urban habitats and effects of urbanization (Schwarzenberger and Dean 2003; Pietersen et al. 2010; Naidoo et al. 2011; Pryke et al. 2011; Symes and Kruger 2012), along riparian corridors (Wyma 2012), and in their role as pollination and fruit dispersal agents (Geerts and Pauw 2012; Pauw and Louw 2012; Mokotjomela et al. 2013). Mammal studies (excluding livestock and the management of baboons, rats and cats, to be mentioned later) include feral cats (Tennent and Downs 2008), baboons (Hoffman and O'Riain 2011; Hoffman and O'Riain 2012a), and bats (Naidoo et al. 2013; Rollinson et al. 2013). Most of the studies on invertebrates are arthropod studies (e.g. Wood and Samways 1991; Steytler and Samways 1995; Pryke and Samways 2009; Pryke et al. 2011; Botha 2012; Anderson et al. 2014), two others included multiple taxonomic groups (Whitmore et al. 2002; McQuaid and Griffiths 2014). Fish, amphibians, reptiles, fungi, algae and bacteria are the most neglected biotic groups in urban ecological studies in South Africa. Four of the studies on fish are limited to the effects of polluted water on two species of fish namely catfish and carp (Marchand et al. 2009; van Dyk et al. 2009; Pieterse et al. 2010; Olowoyo et al. 2012). Two others focused on anthropogenic effects on fish behaviour in estuaries (Becker et al. 2013a; Becker et al. 2013b). Only one amphibian study by Davies et al. (2013) was found; however, the study included farms as well. The other studies mentioning amphibians either only give the number of species or mention the endemic species found in the study area (Rebelo et al. 2011; Holmes et al. 2012; Goodness and Anderson 2013) and one other study listed two amphibian species as part of utilized wild-harvested species in Cape Town (Petersen et al. 2012).

Reptiles are represented by two studies, namely one on Cape dwarf chameleons (Katz et al. 2014) and one on tree agamas (Whiting et al. 2009). Other studies mentioning reptiles list endangered species occurring in the area under scrutiny (Swilling et al. 2012) or in describing the biodiversity of Cape Town (Rebelo et al. 2011; Holmes et al. 2012; Goodness and Anderson 2013), and which species are harvested for utilization (Petersen et al. 2012). Only four studies mentioning fungi was found. Van der Walt et al. (2007) did a study on the levels of the toxic fungus *Fusarium* in household food gardens. Jansen van Rensburg (2010) determined soil fungal levels along an urbanization gradient; however, the individual species were not identified. Ward (1980) lists a few fungal parasites found in the Isipingo Beach area, and Petersen et al. (2012) list three fungi species harvested for use in Cape Town. Research on algae was limited to three studies. García-Rodríguez et al. (2007) did paleolimnological assessments measuring diatoms and chrysophyte cysts in sediment cores to determine the human impacts on a lake. Walsh and Wepener (2009) used diatoms to determine influence of different land use types on river water quality, and Mead et al. (2013) in their review on human-mediated effects on South African coastal systems discuss several marine algae species and the human impact thereon. The only studies investigating bacteria were a study on faecal pollution and antibiotic resistant bacteria in the Mooi river system (Pantshwa 2006) and the study by Jansen van Rensburg (2010) on the microbial diversity of soil.

Studies investigating multiple biotic groups numbered 29. Of these three were urban agricultural studies that included livestock. Two of the studies researched utilization of different biotic groups (Lannas and Turpie 2009; Petersen et al. 2012). Three studies had detailed descriptions of the vegetation habitat whilst sampling other biotic groups (Samways and Steytler 1996; Pryke and Samways 2009; Hoffman and O'Riain 2011). Six of the studies only listed endangered species and or species diversity values of different biotic groups (e.g. Ward 1980; Rebelo et al. 2011; Swilling et al. 2012). Mead et al. (2013) reviewed the biota of coastal ecosystems; Jansen van Rensburg (2010) surveyed bacteria, fungi and vegetation; Van der Walt et al. (2007) surveyed fungi and vegetation; and Whiting et al. (2009) surveyed reptiles and vegetation. Five studies surveyed invertebrates and vegetation (e.g. McGeoch and Chown 1997; Botha 2012; Anderson et al. 2014); two surveyed birds, invertebrates and vegetation (Pryke et al. 2011; Geerts and Pauw 2012); and four surveyed birds and vegetation (Schwarzenberger and Dean 2003; Wilken 2007; van Rooyen 2009; Mokotjomela et al. 2013).

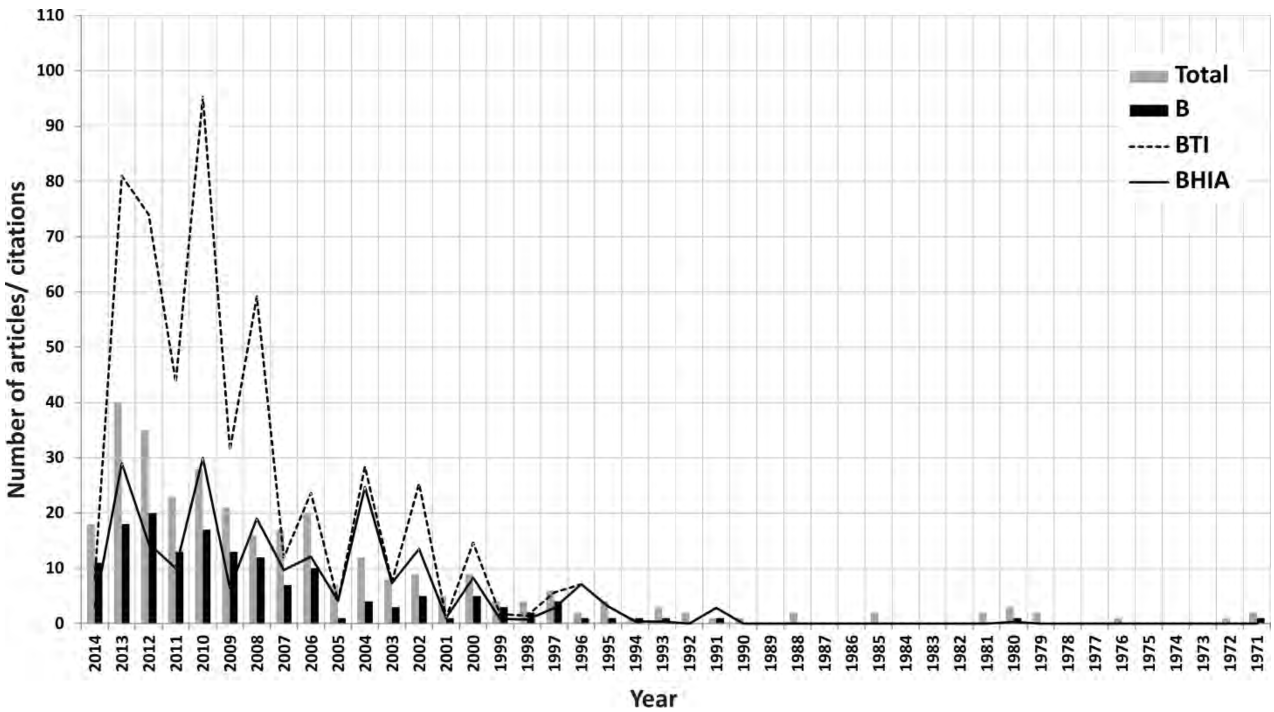

Fig. 5 The number of biodiversity articles published per year (black bars), indicating the total impact of the articles per year (BTI) and the highest impact article for each year (BHIA). Also shown are grey bars representing the total number of all articles per year.

Management

To enhance the relevance of their data most scientists add management and planning recommendations to their research or they specifically design the research to align to planning and management goals (e.g. Pryke and Samways 2009; Schäffler and Swilling 2013; Shackleton et al. 2014). Forty-nine percent of all the articles evaluated referred to management in some capacity. In 2012 and 2013 management themes were by far the most important topic in the South African urban ecological literature (Table 4, Fig. 6). Moreover, all except one of the highest impact articles incorporated management in some way (Table 3), whereas six of the highest citation studies included management (Table 2). The first article incorporating management is an article on urban open space planning by Poynton and Roberts (1985) wherein they reviewed planning and management of urban open spaces in Durban, Johannesburg and Cape Town from an island biogeographical perspective. Initial management approaches focussed on management of planned urban areas (Poynton and Roberts 1985; Wall 1992), environmental management recommendations (Steytler and Samways 1995; Samways and Steytler 1996; Clark and Samways 1997), the potential role of urban agriculture in urban governance (Rogerson 1993; May and Rogerson 1995), waste management (Armitage and Rooseboom 1999), environmental justice and rights (Wisner 1995; McDonald 1997; McDonald 1998), urban environmental hazards (Wisner and Luce 1995), and the effect of management practices on vegetation composition (Cilliers and Bredenkamp 1999).

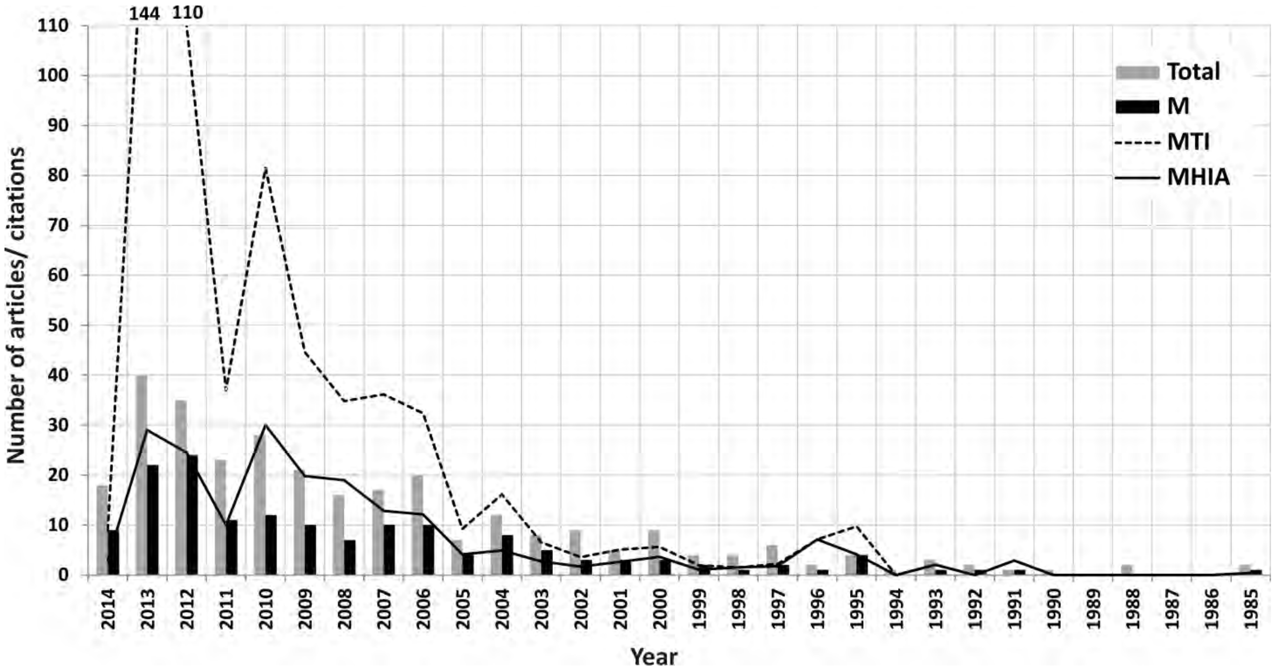

Fig. 6 The number of management articles published per year (black bars), indicating the total impact of the articles per year (MTI) and the highest impact article for each year (MHIA). Also shown are grey bars representing the total number of all articles per year.

Later publications on the above issues include: environmental management recommendations regarding inter alia urban lake rehabilitation (García-Rodríguez et al. 2007); feral cats (Tennent et al. 2009), invertebrate diversity (Pryke and Samways 2009), and coastal dunes (Lucrezi et al. 2014); urban agriculture as a poverty management strategy (Rogerson 2003b; Rogerson 2011); waste management of urban litter (Marais and Armitage 2004; Marais et al. 2004; Armitage 2007); environmental justice and co-management (Debbané and Keil 2004; Scott and Oelofse 2005; Graham and Ernstson 2012; Ernstson 2013); risk assessment (Mgquba and Vogel 2004; Brooks et al. 2010); and vegetation of managed urban open spaces (Putter 2004). General management practices discussed include soil management practices pertaining to urban agriculture (Materechera 2009; Materechera 2011) and garden management (e.g. Botha 2012). Further management themes can be broadly divided into environmental management and urban governance/management aspects. Studied urban environmental management themes include alien plant management (Ackerman and Talbot 2003; Alston and Richardson 2006; Law 2007; van Wilgen 2012); fire management (Forsyth and van Wilgen 2008; van Wilgen et al. 2012); human-baboon conflict management (Hoffman and O'Riain 2012b); rodent control (Jassat et al. 2013); coastal ecosystem management (Mead et al. 2013); ecosystem services (Ernstson et al. 2010; O'Farrell et al. 2011; de Wit et al. 2012; O'Farrell et al. 2012; Cilliers et al. 2013; Ernstson and Sörlin 2013); resource management in the sense of species harvesting and conservation (Botha et al. 2004; Rebelo et al. 2011), community based natural resource management and conservation justice (Kaschula et al. 2005; Ferketic et al. 2010; Taylor and Atkinson 2012);

and integrated environmental management and planning (Pieterse 2004; Cilliers 2009; Cilliers et al. 2011b; Cilliers et al. 2014).
More specific urban governance/management themes include research on municipal commonage management and utilization such as Ingle (2006), Thornton (2009), Davenport et al. (2011), Davenport et al. (2012) and Puttick et al. (2014); public green space management (Shackleton and Blair 2013); urban water management (e.g. Grobicki 2001; Morrison et al. 2001; Saayman and Adams 2002; Carden and Armitage 2013; Fisher-Jeffes and Armitage 2013; Wegelin and Jacobs 2013); the built environment (du Plessis et al. 2003; Goebel 2007; Ross et al. 2010); participatory urban governance (Barnett and Scott 2007a; Barnett and Scott 2007b; Aylett 2010b; Aylett 2010a; Pfeffer et al. 2013); the urban policy agenda (Boraine et al. 2006); management at the rural-urban fringe (Cash 2014); urban environmental governance (Freund 2001) and the new field of urban biodiversity governance (Wilkinson et al. 2013); urban biodiversity management planning (Anderson et al. 2014); and sustainable development (e.g. Oelofse and Patel 2000; Swilling and Annecke 2006; Swilling et al. 2012). The last few years have seen a surge of new research based on climate change and the management implications thereof has not been neglected. More than 15 of the evaluated publications are dedicated to the novel topic of urban climate governance, mostly concerning mitigation and adaptation strategies (e.g. Holgate 2007; Mukheibir and Ziervogel 2007; Carmin et al. 2012; Faling et al. 2012; Aylett 2013; Cartwright et al. 2013; Fatti and Patel 2013; Pasquini et al. 2013; Bulkeley et al. 2014; Pasquini et al. 2014)

Conservation

Theodore Roosevelt, in an address in 1907, definitively declared his position on the importance of conservation by stating that "*the conservation of natural resources is the fundamental problem. Unless we solve that problem it will avail us little to solve all others*." In South Africa, conservation remains a fundamental theme, aspects of it being researched in all the years since 1994 (Table 4). However, in only seven of those years has it contributed to more than 50% of the total impact, and since 2000 only three times. In 2013, conservation scored a mere 31% of the total impact (Table 4). Only 36% of all the evaluated research incorporates conservation, of which only 12% of the 114 conservation publications include the term conservation in the title. Figure 7 illustrates the development and contribution of conservation research. Only three of the highest citation articles included conservation (Table 2) and only four of the highest impact articles (Table 3). The earliest publication that discussed conservation issues was the previously mentioned urban open space planning article by Poynton and Roberts (1985). Therein, they advocate the incorporation of conservation areas together with all other open spaces into open space networks.

Conservation has been approached in various ways in the urban ecological literature. Basic themes include overviews of the state of nature conservation, e.g. insect conservation (McGeoch 2002) and urban nature conservation in general (Cilliers et al. 2004); the need to protect endangered or vulnerable species such as the black eagle in an urban environment (Symes and Kruger 2012), vulture conservation efforts (Naidoo et al. 2011), incorporating protection of areas hosting endangered species in planning efforts (Donaldson-Selby et al. 2007); research on the ecology of an endangered endemic geophyte in an urban setting (Geerts and Pauw 2012); and research on chameleons in a critically endangered ecosystem (Katz et al. 2014). Cape Town, due to its unique setting inside a highly diverse floral kingdom, is the most important city in South Africa in terms of conservation research and is also the only city in South Africa to include a National Park within its borders, the Table Mountain National Park. Specific studies on the conservation of Cape Town's biodiversity include Rebelo et al. (2011), Holmes et al. (2012), Goodness and Anderson (2013), and an

account of the ecological history of the city (Anderson and O'Farrell 2012). Furthermore, van Wilgen et al. (2012) and van Wilgen (2012) specifically focus on the Table Mountain National Park.
Whilst not explicitly doing the research for conservation reasons, many researchers state that their research is carried out as baseline ecological data documenting diversity and community structure in various locations which can be used as input for conservation applications (e.g. van Wyk et al. 1997; Cilliers et al. 1998; Cilliers et al. 1999; Grobler et al. 2006; Daemane et al. 2010; Dingaan and du Preez 2013; Meek et al. 2013). Another way of reasoning regarding the traditional conservation argument emerged with the realization of the cultural value of nature, as the "*recognition of the cultural and spiritual values associated with wild plants would greatly enhance biodiversity conservation efforts*" (Cocks and Dold 2006). Publications on this aspect include Cocks and Wiersum (2003), Kaschula et al. (2005) and Philander et al. (2011). However, the cultural exploitation of natural resources for medicinal and other purposes often includes rare and endangered species. Therefore, the conservation concerns raised in these studies are traditional in the sense that specific utilized species need to be conserved from overexploitation and extinction for its uniqueness and vulnerability regardless of its cultural use value (Matsiliza and Barker 2001; Dold and Cocks 2002; Botha et al. 2004; Petersen et al. 2012; Petersen et al. 2014).

The impacts of man on biodiversity and the subsequent conservation concerns are another researched theme. Research is carried out on the impact and repercussions of invasive alien plants (Alston and Richardson 2006; Law 2007; Dures and Cumming 2010; van Wilgen 2012); the effect of informal settlements on the integrity of local vegetation types (Berry et al. 1994); impacts on bird functional diversity (Pauw and Louw 2012); human-baboon conflicts (Hoffman and O'Riain 2012a), coastal ecosystems (Mead et al. 2013) and specifically coastal dune vegetation (Lucrezi et al. 2014); changes in grassland ecology along an urban-rural gradient (du Toit 2009); and the effects of land use on riparian vegetation (Meek et al. 2010). This directly relates to conservation management applications such as ecological landscaping recommendations to maximize biodiversity conservation (Wood and Samways 1991; Steytler and Samways 1995; Samways and Steytler 1996; Clark and Samways 1997), and urban conservancy management practices (Tennent and Downs 2008; Tennent et al. 2009). Conservation is incorporated in planning research (Wall 1992; Todes 2004; Cilliers and Drewes 2010) and listed as a reason for maintaining public green spaces (Shackleton and Blair 2013). Furthermore, many studies show the significance and contribution of remnant or created urban habitat patches (green spaces) to biodiversity conservation, e.g. urban habitat patches and reserves contribute to persistence of moth assemblages in urban areas (McGeoch and Chown 1997); structurally enhanced road islands support many invertebrate species (Whitmore et al. 2002); villages act as refugia for local bird diversity (van Rooyen 2009); botanical gardens play a major role in conservation of species in urban areas (Ward et al. 2010); gardens as refugia for endangered birds (Pryke et al. 2011); and the contribution of fragmented grassland patches to the green infrastructure of cities (van der Walt et al. 2015). Moreover, contemporary studies on urban gardens have emerged as often ignored unconventional and surprising spaces of biodiversity conservation (Davoren 2009; Lubbe et al. 2011; Botha 2012; Molebatsi et al. 2013). However, modification of natural areas and abundance of similar urban habitats can have unintended consequences as well, as documented by the range expansion of an invasive indigenous amphibian by means of farm dams (Davies et al. 2013).

The sustainability discourse has also relied on conservation ethics in promoting sustainability and often "*sustainable development is focused on conservation of the environment*" (Kruger 2006). Authors who included conservation concerns in their sustainable development arguments include Oelofse and Patel (2000), Kruger (2006), Swilling (2010), and Swilling et al. (2012). Research tools and methods developed to assist in conserving or emphasising the importance of biodiversity as conservation goals, include the approach of urban biotope mapping (Cilliers et al. 2004; Drewes and Cilliers 2004; Putter 2004), avitopes (Smith 2004), resource economics or ecosystem services valuation (Roberts et al. 2005; O'Farrell et al. 2011; Schäffler 2011; O'Farrell et al. 2012; Ernstson and Sörlin 2013), ecosystem based adaptation (Roberts et al. 2012), and systematic conservation planning (e.g. Roberts and O'Donoghue 2013; Wilhelm-Rechmann et al. 2014). Conservation is mainly related to conservation of biodiversity and almost all of the studies included here alluded to that, however a study focused on water conservation, in the sense of a sustainable water supply and reducing water losses (Wegelin and Jacobs 2013) and another discussed it in an argument on environmental justice (Debbané and Keil 2004).

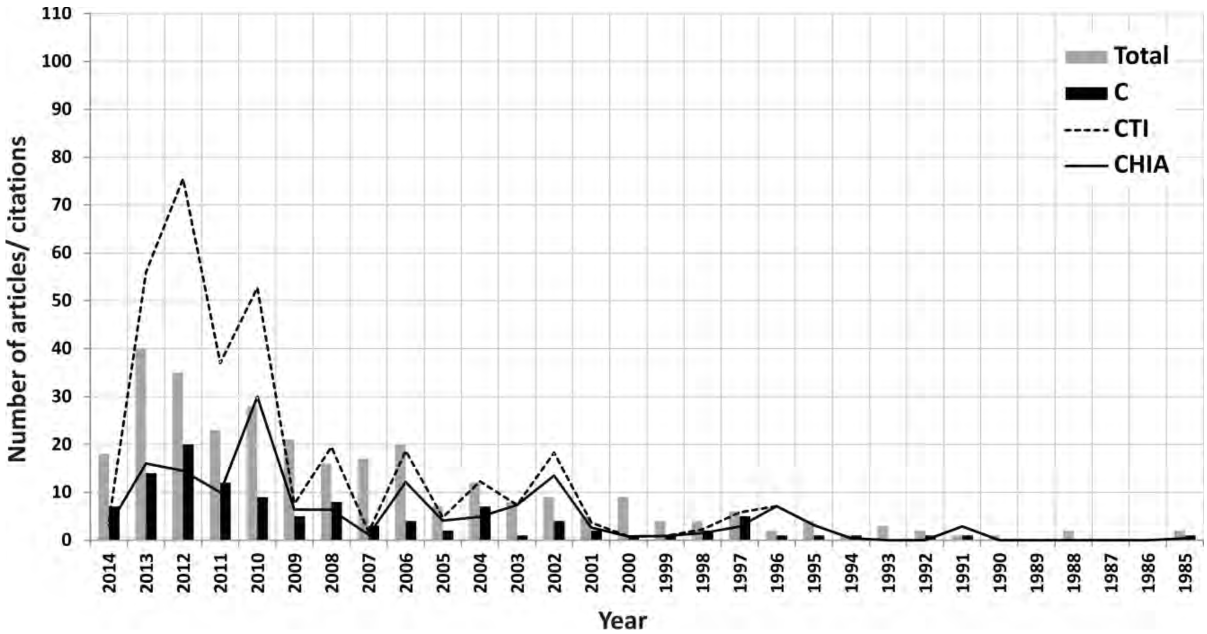

Fig. 7 The number of conservation articles published per year (black bars), indicating the total impact of the articles per year (CTI) and the highest impact article for each year (CHIA). Also shown are grey bars representing the total number of all articles per year.

Conservation has not been without its controversy. A close scrutiny of Table 4 indicates the overall decline in the percentage total contribution of publications on conservation concerns since 2000, despite increases in the number of publications published on the subject. A credible explanation is the varying public sentiment held by contemporary post-Apartheid South Africans on conservation. Whyte (1995) aptly states that "*the environment also suffers from a perception that it is a white, middle-class issue focused on nature conservation, that it is not relevant to the urgent needs of the country for development and social justice*" and furthermore, "*the preservation of nature is regarded as fundamentally in opposition to socio-economic development. Conservation is frequently interpreted as being a socially unjust endeavor, disrespectful toward people and lacking realism*." (Wilhelm-Rechmann and Cowling 2011). Subsequently, a 'brown' and 'green' agenda have emerged in South Africa. Proponents of a shift from green to brown such as Freund (2001) state that "*all too often, 'environmentalism' still operates effectively as a conservation strategy that engages very little with the actual needs and possibilities of poor people*". McDonald (1997); McDonald (1998) highlights the fact that some see the environment only in terms of conservation ignoring the 'brown' environmental crisis, specifically the reality of inadequate service delivery and unhealthy living conditions faced by many.

In recognizing those issues but retaining the importance of conservation of nature arose concepts such as conservation justice advocating that "*local communities are entitled to receive fair treatment and* *meaningful involvement in the development and implementation of conservation policy*" (Ferketic et al. 2010). In their study on the Macassar Dunes Conservation Area, Ferketic et al. (2010) emphasize the use of community-based conservation themes. Further advocates of involving civil society in nature conservation and co-management approaches include Ernstson et al. (2010), Graham and Ernstson (2012) and Anderson et al. (2014). More critically, to ensure survival and sustained relevancy the managers of the Abe Bailey Nature Reserve have turned to delivering benefits to the local surrounding urban community (Taylor and Atkinson 2012). Whereas, Wilhelm-Rechmann and Cowling (2011) expound on ways to incorporate and relativize biodiversity into municipal decision-making processes. Additionally, communicating conservation principles through education has also been researched (e.g. Le Maitre et al. 1997; Philander et al. 2011). In their research on socioecological theory, focussing on coupled human and natural systems in a rapidly urbanizing area bordering the Kruger National Park, McHale et al. (2013) state that research in such rapidly urbanizing regions might provide "*new solutions to the contradictions that exist between the conservation of biodiversity and the livelihoods of people*".

Planning

Planning is a fundamental aspect of any government or country. However, only 29% of the evaluated publications researched or discussed planning themes. Planning has not been a very popular theme in urban ecological studies in South Africa, for only four of the years planning contributed more than 50% of the total impact (Table 4, Fig. 8). In 1995 only four publications were produced of which two were planning publications contributing 58% of the total impact for that year. In both 2010 and 2013, one publication is responsible for a contribution of more than 50% for those years. The publication of Ernstson et al. (2010) represent 22% of the total impact for that year, and Ernstson (2013) represents 16% for the total impact (Fig. 8), both are part of the top ten highest impact articles list (Table 3) and Ernstson et al. (2010) is also listed in the top ten highest citations (Table 2).

The earliest planning theme focusing on environmental concerns was the publication of Poynton and Roberts (1985) on urban open space planning. Another publication touching on this subject is that of Wall (1992) on the competition between development and open spaces in urban areas. The first publication to address the issue again is the publication of Donaldson-Selby et al. (2007) on visualisation tools to enable public participation in urban greening plans. Thereafter publications include urban green space planning (Sutton 2008; Cilliers 2009; Anderson et al. 2014; Shackleton et al. 2014), public green space (McConnachie et al. 2008; McConnachie and Shackleton 2010; Shackleton and Blair 2013), street tree distribution (Kuruneri-Chitepo and Shackleton 2011), and planning of the contemporary concept of the total green infrastructure (Schäffler 2011; Cilliers et al. 2013; Schäffler and Swilling 2013). More general spatial planning themes incorporating environmental concerns include environmental policy and planning (Freund 2001; Pieterse 2004; Patel 2005; Cilliers et al. 2009; Cilliers et al. 2011b), land use planning policies restricting litter producing activities (Marais and Armitage 2004; Armitage 2007) and municipal commonage land use planning (Ingle 2006; Thornton 2009), city region planning (van Huyssteen et al. 2009), eco-estate development (Ballard and Jones 2011), and groundwater management and planning (Riemann et al. 2012). Additionally, Watson (2009) wrote an influential review paper on urban planning in the 21st century urbanization context, specifically focused on pro-poor reformatory planning themes.

Alternative urban planning themes include: advocating the inclusion of urban agriculture into formal planning strategies (e.g. Rogerson 1993; May and Rogerson 1995; Rogerson 2003b; Reuther and Dewar 2006; Swilling 2010; Rogerson 2011); counter-disaster planning (Wisner and Luce 1995); and conservation planning of which systematic conservation planning is the most prominent (Rebelo et al. 2011; Holmes et al. 2012; Wilhelm-Rechmann et al. 2014). Other conservation planning research includes co-management and participatory conservation planning (Ferketic et al. 2010; Graham and Ernstson 2012), and the work carried out on ways to reframe biodiversity and conservation issues to be relevant, accepted and used by municipal stakeholders (Wilhelm-Rechmann and Cowling 2011; Wilhelm-Rechmann and Cowling 2013). Moreover, social and environmental justice in planning processes (Scott and Oelofse 2005) and proponents of participatory planning are of increasing importance in contemporary democratic contexts (Aylett 2010b; Aylett 2010a; Pfeffer et al. 2013). The boom of the sustainable development discourse found its way into planning practices and recommendations, and subsequent importance of planning for sustainable development is propounded by many researchers (e.g. Oelofse and Patel 2000; Roberts and Diederichs 2002; Todes 2004; Kruger 2006; Swilling 2006; Swilling and Annecke 2006; Ross et al. 2010; Swilling 2010; Musakwa and Niekerk 2013; Cilliers et al. 2014).

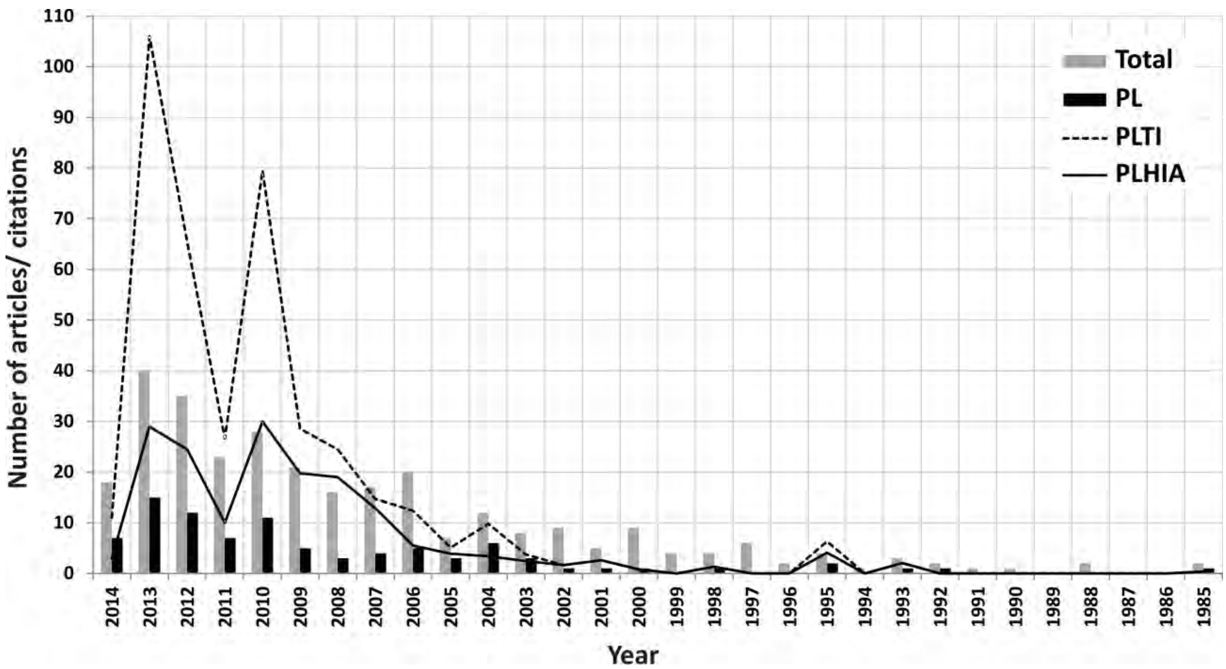

Fig. 8 The number of planning articles published per year (black bars), indicating the total impact of the articles per year (PLTI) and the highest impact article for each year (PLHIA). Also shown are grey bars representing the total number of all articles per year.

Parallel to the sustainable development discourse are the overwhelming climate change realities which currently dominates global scientific research. Planning themes followed suit and the focus clearly switched from sustainable development towards municipal climate change adaptation planning strategies (Roberts 2008; Roberts 2010; Ziervogel et al. 2010; Carmin et al. 2012; Faling et al. 2012; Mather and Stretch 2012; Roberts et al. 2012; Pasquini et al. 2014). In 2013 alone six publications discussed climate change planning strategies (Aylett 2013; Cartwright et al. 2013; Fatti and Patel 2013; Ogundeji et al. 2013; Pasquini et al. 2013; Roberts and O'Donoghue 2013). Notwithstanding the sustainable development or the climate change discourse another concept has stealthily gained standing and recognition, namely that of resilience. Again, planning themes reciprocated and a highly influential publication was published on planning for urban resilience by Ernstson et al. (2010) (Tables 2,3), other publications incorporating resilience in planning include Roberts (2010) and Schäffler and Swilling (2013). Lastly, several publications report on spatial planning tools, such as urban biotope mapping (Cilliers et al. 2004; Drewes and Cilliers 2004; Putter 2004; Wilken 2007), resource economics later called ecosystem services valuation (Roberts et al. 2005; Cilliers et al. 2013; Ahern et al. 2014), land-use suitability modelling (Cilliers and Drewes 2010), and the use of remote sensing technologies (Odindi et al. 2012; Odindi and Mhangara 2012).

Human needs

In South Africa, the number of people living in poverty in 2011 was 45.5% (Statistics South Africa 2014). Rogerson (1993) declares that "*in urban Africa subsistence cultivation is widely interpreted as an essential component of everyday survival*". The human needs theme includes that of urban agriculture, medicinal plants, and utilization of trees for firewood and other uses. Twenty-four percent of the evaluated publications incorporated human needs aspects. Since 2004, there was a steady decline in the impact of publications researching this theme (Fig. 9). In 2013 only five publications included this theme with these scoring nine percent of the total impact for articles of that year (Table 4). Despite its low overall prevalence in South African urban literature (Table 4, Fig. 9), three of the publications on human needs have been very influential, namely: the publication of Shackleton and Shackleton (2004) on the utilization of non-timber forest products by rural inhabitants. This publication is ranked first on the list of publications scoring the highest number of citations (Table 2) and third on the articles with the highest impact of the evaluated publications (Table 3). Secondly, the publication by Dold and Cocks (2002) on medicinal plant usage in the Eastern Cape, ranked second in the highest number of citations (Table 2). Finally, Williams et al. (2000) wrote a paper on the commercial market for medicinal plants in the Witwatersrand urban agglomeration which ranked sixth in the highest citations list (Table 2).

Rogerson (1993) states that urban agriculture gained importance and recognition on the policy agenda as a sustainable development strategy and specifically to enhance the sustainability of cities. It "*is increasingly seen as a major means of supplementing incomes in the cities of South Africa*" (May and Rogerson 1995). In an answer to this many studies have focused on urban agriculture as a means to alleviate poverty and in determining its effectiveness as livelihood strategy (e.g. Slater 2001; Rogerson 2003b; Reuther and Dewar 2006; van Averbeke 2007; Phiri 2008; Shackleton et al. 2010; Swilling 2010; Rogerson 2011; Swilling et al. 2012; Magidimisha et al. 2013). Over the years, however, doubt has also been levelled at the real benefit of urban agriculture as a successful livelihood strategy, sparking many debates (Rogerson 1998; Thornton 2008; Ruysenaar 2012). In discussing this debate Webb (2011) argues that "*without clarity on the benefits and significance of urban agriculture, current and potential cultivators face high levels of uncertainty and risk*".

The use of plants and animals in household remedies has fascinated researchers for years as evidenced by the book of Pappe (1850) on economic botany. Moreover, studies have shown the importance of indigenous biodiversity in cultural practices (Dold and Cocks 2000; Cocks and Dold 2006). Lately an urgency has developed to document the indigenous knowledge of native tribes on medicinal plants and other uses before it is lost (e.g. Matsiliza and Barker 2001; Van Wyk et al. 2008) as well as in documenting the role and effectiveness of education and knowledge transference in preserving indigenous knowledge of plant uses (Zobolo and Mkabela 2006; Philander et al. 2011). Moreover, knowledge of traditional uses of plants has fuelled the large scale use thereof in the formal natural products sector (Makunga et al. 2008). However, urbanization and population growth greatly escalated the trade in medicinal plants in urban centres some of which have reached alarming proportions threatening local sustainability and survival of species. Philander et al. (2011) state that the "*use of medicinal plants in South Africa is increasing and reinforced through pervasive traditional belief systems*". As a result, many studies concentrated on the scale and impacts of trade in fauna and flora and also on compiling lists of the species utilized (e.g. Dauskardt 1990b;

Williams et al. 1997; Williams et al. 2000; Dold and Cocks 2002; Botha et al. 2004; Makunga et al. 2008; Petersen et al. 2012; Petersen et al. 2014).

In South Africa, many depend on trees for firewood and other non-timber forest products. Poverty and the limited availability of electricity force a reliance on trees to provide firewood for household use and much research is devoted to the impacts, utilization, trade and sustainability thereof (e.g. Banks et al. 1996; Cilliers et al. 1999; du Plessis et al. 2003; Kaschula et al. 2005; Shackleton et al. 2006; Madubansi and Shackleton 2007; Whiting et al. 2009; Kimemia and Annegarn 2011; McHale et al. 2013; Kaoma and Shackleton 2014). The utilization and importance of non-timber forest products have been documented by Cocks and Wiersum (2003), Shackleton and Shackleton (2004) and Kaoma and Shackleton (2014). Lastly, the effectiveness of education strategies on the importance of trees has received scrutiny by Parkin et al. (2006).

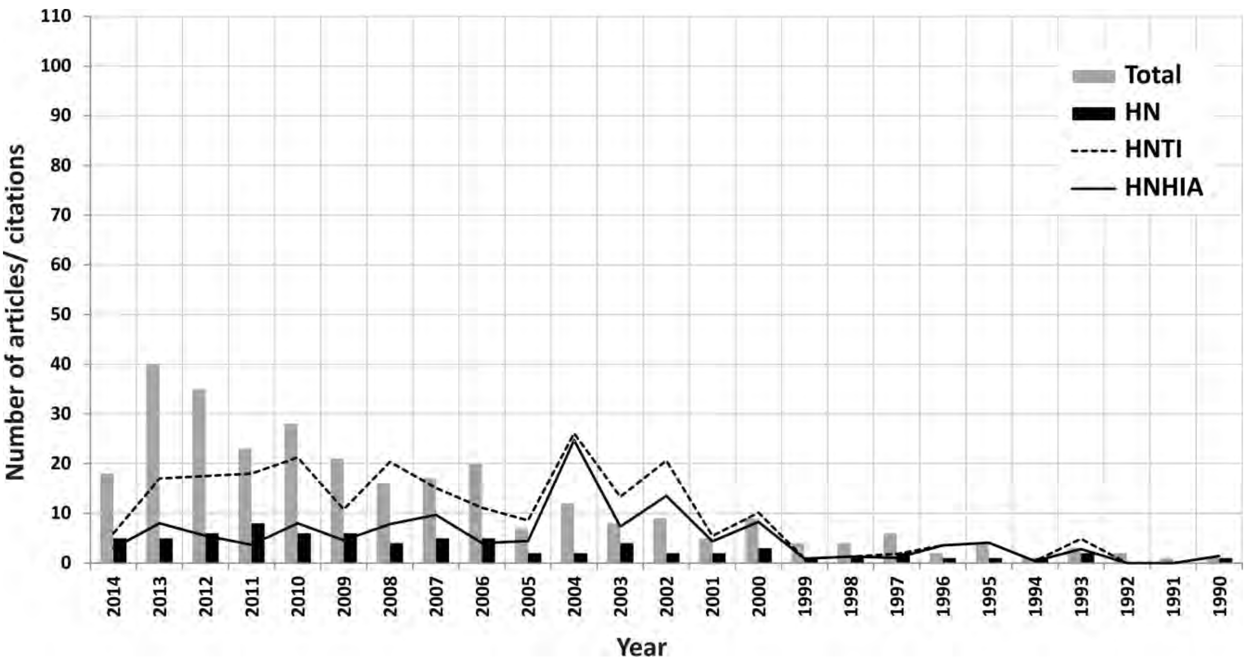

Fig. 9 The number of human needs articles published per year (black bars), indicating the total impact of the articles per year (HNTI) and the highest impact article for each year (HNHIA). Also shown are grey bars representing the total number of all articles per year.

Sustainability

"*Sustainable development is a way of talking about the future shape of the world. To conceive of the future in these terms marks the beginning of a process of political reflection and action, not the end. To call for sustainable development is not to set out a blueprint for the future but to issue a statement of intent and a challenge to action*" (Adams 2009). Of the evaluated publications 39% incorporate sustainability themes, regularly contributing to more than 50% of the impact per year (Table 4). In 2004, twelve publications were written on urban ecological issues of which nine included sustainability representing 91% of the total impact for articles published that year (Table 4, Fig. 10). The first article that included sustainability was by Rogerson (1993) on urban agriculture as a strategy for sustainable development, in the sense of alleviating poverty through food production. Further research on the value of urban agriculture as a sustainability strategy include May and Rogerson (1995), Rogerson (1998), Webb (2011) and by Davoren (2009) through specific research carried out on home garden plant diversity. An additional development on this issue emerged with the concept of the sustainable livelihood theme, and most subsequent publications on urban agriculture are framed within this context (Rogerson 2003b; Phiri 2008; Thornton 2008; Faber et al. 2010; Rogerson 2011; Magidimisha et al. 2013) as well as a publication on the utilization of non-timber forest products by Shackleton and Shackleton (2004) (Tables 2 and 3).

Sustainability is a wide and flexible term used indiscriminately by many (Patel 2005; Kruger 2006) and has been framed in multiple ways in the South African literature. The themes researched include: the sustainable utilization of natural resources (e.g. Banks et al. 1996; Dold and Cocks 2002; McGeoch 2002; Shackleton and Shackleton 2004; Kaschula et al. 2005; Makunga et al. 2008; Lannas and Turpie 2009; Davenport et al. 2011; Petersen et al. 2012); equity and environmental sustainability of marginalized communities, in sense of environmental justice (McDonald 1998; Oelofse and Patel 2000; Debbané and Keil 2004; Scott and Oelofse 2005; Barnett and Scott 2007a; Scott and Barnett 2009); and to promote conservation, i.e. ecological sustainability (Le Maitre et al. 1997; Cilliers et al. 2004; Smith 2004; Wilhelm-Rechmann and Cowling 2011). Moreover, the importance of supplying community benefits and ensuring community participation in conservation areas to ensure the long term sustainability and survival of such areas were dealt with (Ferketic et al. 2010; Taylor and Atkinson 2012). Some have specifically used the concept of ecosystems services to promote a sustainable conservation agenda, in the sense of protecting a sustainable supply of ecosystem services (Roberts et al. 2005; O'Farrell et al. 2012; Schäffler and Swilling 2013). Le Maitre et al. (2007) in particular expound on the usefulness of ecosystem services as an overarching research theme to promote sustainability science.

The most significant and profuse contribution to the sustainability discourse is that of sustainable cities and ways to promote and ensure it. In his address to the Conference on Sustainable Urban Development, Kofi Annan aptly stated that "*the future of humanity lies in cities*" (United Nations 2002). The main departure point of the debate around sustainable development in South African cities is that of environmental policies and the implementation thereof (Freund 2001; Patel 2005; Boraine et al. 2006; Sutton 2008). In Durban, a comprehensive Local Agenda 21 programme was implemented (e.g. Roberts and Diederichs 2002; Roberts 2003). Another city, Midrand became Africa's first eco-city due to its implementation of 'eco-development' in planning (Rogerson 2003a). In Stellenbosch, another example of mainstream sustainable implementation strategies is the Lynedoch EcoVillage, described as "*the first intentional, socially mixed ecologically designed urban development in the South African context*" (Swilling and Annecke 2006). Urban sustainability as the main research aim was studied by Kruger (2006) and Smit and Parnell (2012) in combination with health issues. Moreover, Stellenbosch and Cape Town were the subjects of two books entirely on sustainability and its current status in all urban sectors of these two urban areas (Swilling 2010; Swilling et al. 2012). The sustainable development context is also used on the issue of mass low cost housing provisioning (Goebel 2007; Ross et al. 2010), as well as the urban greening initiatives or lack thereof associated with it (Shackleton et al. 2014). Furthermore, Pieterse (2004) has written critically on urban integration and its current status as a sustainable urban development strategy.

The incorporation and implementation success of sustainability into spatial planning have also received attention (Todes 2004; Swilling 2006; Cilliers 2009; Watson 2009). Particularly the description of tools to assist in this objective, such as biotope mapping (Drewes and Cilliers 2004), land use suitability modelling (Cilliers and Drewes 2010), remote sensing technologies (Odindi et al. 2012; Musakwa and Niekerk 2013), ecosystem services valuation (Roberts et al. 2005), and photorealistic visualization tools (Donaldson-Selby et al. 2007). Sustainable urban management strategies include: sustainable litter reduction (Marais and Armitage 2004); energy efficiency (Nel 2006); sustainable water supply, quality and management (Morrison et al. 2001; Riemann et al. 2012; Carden and Armitage 2013; Wegelin and Jacobs 2013); sustainable alien plant management (Law 2007); sustainable land-use management through the use of ecosystem services (O'Farrell et al. 2011); and sustainable stormwater management (Owusu-Asante and Ndiritu 2009).

Unsurprisingly, in the face of the current consensus on predicted climate change realities, the discourse of sustainability and the responsibility of reducing vulnerability to climate change scenarios have met. These include: assessing the role of the built environment (du Plessis et al. 2003), role of stakeholders in mitigation strategies (Holgate 2007), and municipal level adaptation strategies (Mukheibir and Ziervogel 2007; Roberts 2008; Roberts 2010; Carmin et al. 2012; Faling et al. 2012). Lastly, the role of resilience and sustainability (Ernstson et al. 2010), and that of the need for transdisciplinary perspectives in answering complex sustainability challenges (Goebel et al. 2010; Cilliers et al. 2014) have also emerged.

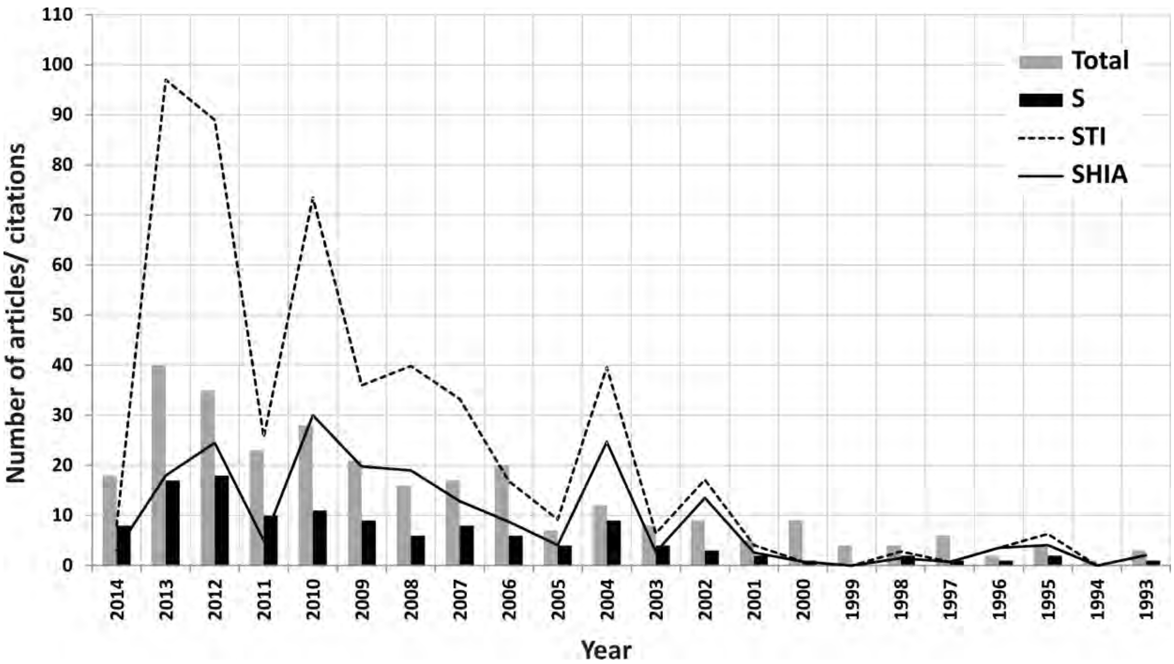

Fig. 10 The number of sustainability articles published per year (black bars), indicating the total impact of the articles per year (STI) and the highest impact article for each year (SHIA). Also shown are grey bars representing the total number of all articles per year.

Public participation

Urban ecology "*as an interaction between humans and nature*" (Marzluff et al. 2008a) by implication necessitates the inclusion of a human component in any related research question. Furthermore, civic collaboration is gaining contemporary importance, especially in advocating transdisciplinary themes to real-world problem solving. To determine the tangible role of civic interaction with science the inclusion of science people interactions in the research methodologies were noted. Public participation themes are represented by 47% of the 314 evaluated publications, of which 71% (104 publications) directly garnered public input into their research findings through the use of surveys, questionnaires and interviews as part of their research methodology (e.g. Slater 2001; Zobolo and Mkabela 2006; Van Wyk et al. 2008; Whiting et al. 2009; Ward et al. 2010; Shackleton and Blair 2013). In terms of the contribution to the total citation impact per year, articles featuring public participation themes contributed to more than 50 % of the impact for 12 of the 25 years shown in Table 4, in 2013 it had the second highest impact (Table 4, Fig. 11) and in 2014 it had the highest contribution and number of publications to date (Table 4). Of the 12 publications published in 2014, eight of them incorporated public participation in the form of questionnaires or interviews. The first publications evaluated to include public interactions are discussions with residents on township hazards (Wisner 1995; Wisner and Luce 1995) and the publication by May and Rogerson (1995) on urban cultivation wherein they did household surveys and conducted structured interviews with community participants. More formal participation themes include the emerging concepts of civic ecology (Ernstson et al. 2010; Anderson et al. 2014), civic science (Barnett and Scott 2007a; Scott and Barnett 2009; Pauw and Louw 2012; Pfeffer et al. 2013; Ahern et al. 2014), conservation justice (Ferketic et al. 2010), environmental justice (e.g. Scott et al. 2002; Debbané and Keil 2004; Scott and Oelofse 2005; Leonard and Pelling 2010; Leonard 2011; Ernstson 2013), and political ecology (McDonald 1998; Leonard 2012). Bäckstrand (2003) states that "*the notion of civic science, which is rather vague and elusive, serves as an umbrella for various attempts to increase public participation in the production and use of scientific knowledge*". Civic ecology, conversely, pertains to residents specifically participating and contributing to ecological projects such as tree planting and greening projects in New Orleans (Ernstson et al. 2010).

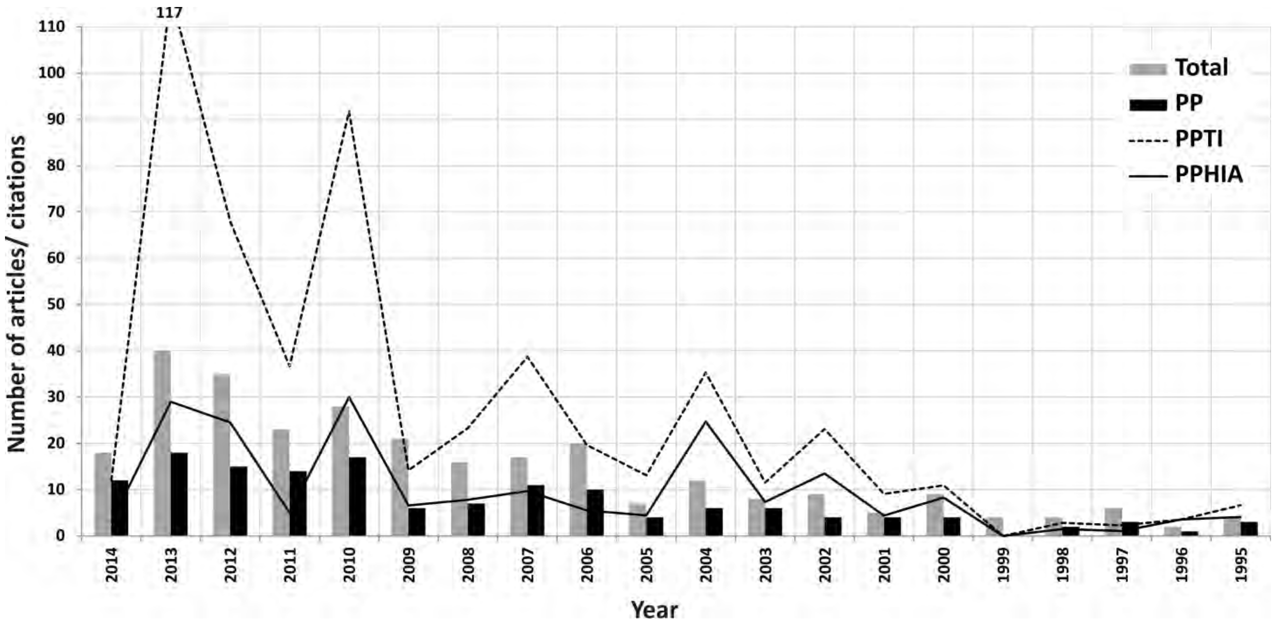

Fig. 11 The number of public participation articles published per year (black bars), indicating the total impact of the articles per year (PPTI) and the highest impact article for each year (PPHIA). Also shown are grey bars representing the total number of all articles per year.

Ecosystem services

"*Ecosystem services are the benefits people obtain from ecosystems*" (Millennium Ecosystem Assessment 2003). Gómez-Baggethun et al. (2010), in their publication on the history of the concept of ecosystem services, state that it emerged in the 1970s with the major mainstreaming thereof after the release of the Millennium Ecosystem Assessment (2003). This publication classifies ecosystem services into regulating, provisioning, supporting, and cultural services. In the evaluation of publications, the theme of ecosystem services was limited to those publications directly mentioning ecosystem services throughout and those measuring it directly. Therefore, even though all the publications on human needs can be classified as provisioning services only those explicitly researching it from an ecosystem services context were included. Figure 12 illustrates the comparative contribution and growth of ecosystem service themes in South Africa. The earliest evaluated publication to use the concept of ecosystem services is the publication of Roberts et al. (2005) on the benefit of calculating monetary values for the services provided by open spaces to supply economic evidence of the importance of conserving open spaces to stakeholders and urban planners in Durban.

The rest of the discussion is structured around where and how the concept of ecosystem services is used in the South African urban literature. Monetary and non-monetary valuating of ecosystem services are advocated as a useful tool in urban open space planning (Roberts et al. 2005; Cilliers et al. 2013; Ahern et al. 2014). Trees provide important ecosystem services, and research includes the monetary value of *Acacia karroo* trees in an urban environment (Pelser 2006); the regulating service of carbon storage and sequestration by trees (Wilken 2007; Stoffberg et al. 2010; O'Donoghue and Shackleton 2013; Schäffler and Swilling 2013); and research carried out on urban greening via the use and perception of trees by residents (Shackleton et al. 2014). In a study on alien plant control, the cost of water hyacinth control was evaluated against the value of water provisioning services (Law 2007). Further examples include: the provisioning services of wetlands (Lannas and Turpie 2009), ecosystem services provided by a municipal commonage (Davenport et al. 2012), advocating conservation through the use of ecosystem services valuation (O'Farrell et al. 2011; Davenport et al. 2012; O'Farrell et al. 2012), and the pollination service by birds (Pauw and Louw 2012). Ecosystem services rendered by the entire urban green infrastructure were scrutinized by Schäffler (2011), Swilling et al. (2012), Cilliers et al. (2013), and Schäffler and Swilling (2013). Additionally de Wit et al. (2012) focused on how to incorporate it into economic decision-making.

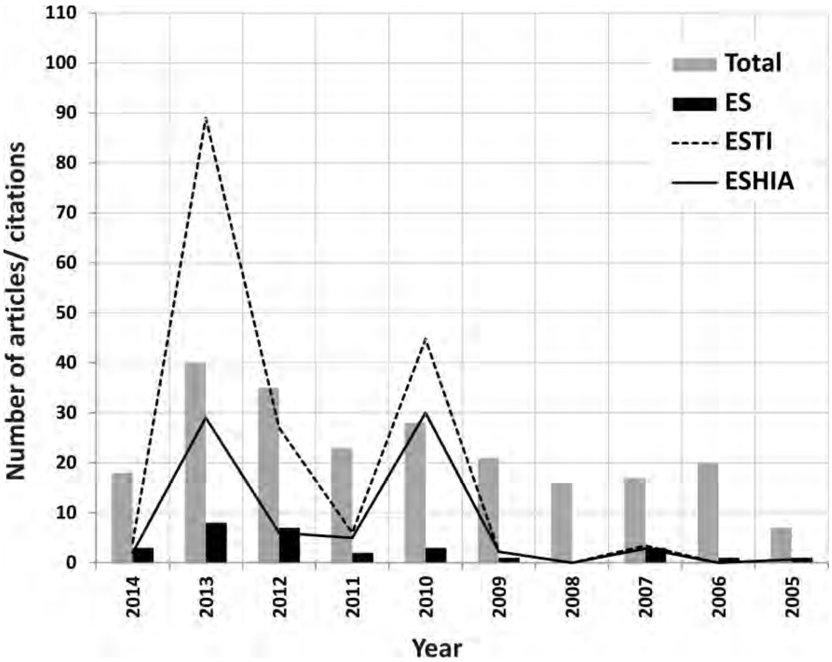

Fig. 12 The number of ecosystem services articles published per year (black bars), indicating the total impact of the articles per year (ESTI) and the highest impact article for each year (ESHIA). Also shown are grey bars representing the total number of all articles per year.

A few overviews were written on ecosystem services in South Africa and especially in Cape Town. In a publication on the role that ecosystem services can play in sustainability science, Le Maitre et al. (2007) were the first to do an overview on ecosystem services publications published on South Africa. Their publication covered all ecosystem services research carried out and it did not exclusively focus on urban areas. However, in a special issue on Cape Town, Anderson and O'Farrell (2012) discussed the history of Cape Town and how the focus on different ecosystem services provided changed through the years, whilst Cilliers and Siebert (2012) wrote the overview on the special issue publications listing ecosystem services as one of the dominant themes followed in Cape Town. Furthermore, Cape Town was also one of the focal cities (Goodness and Anderson 2013) in a recent book entitled *Urbanization, biodiversity and ecosystem services: Challenges and opportunities* (Elmqvist et al. 2013). In another chapter in the same book Wilkinson et al. (2013) wrote the first review on the new field of urban governance of biodiversity and ecosystem services. Theoretical research on ecosystem services include the publication by Ernstson et al. (2010) on sustaining ecosystem services through building resilience; an ecosystem services framework for investigating environmental justice (Ernstson 2013); and in their publication on "*why advanced socioecological theory needs Africa*", McHale et al. (2013) details the global importance of using African livelihood frameworks to illuminate future urbanization thinking and how general questions on ecosystem services are alternatively framed and valued through livelihood paradigms. Additionally, Ernstson and Sörlin (2013) wrote a critical evaluation of ecosystem services and its global contextual setting, putting emphasis on the fact that "*ecosystem services are socially and culturally embedded*" (Ernstson and Sörlin 2013) emphasizing that universal comparisons lose sight of the way in which the social setting impacts the way it is locally valuated.

Resilience

One of the latest themes on the current global ecological agenda is 'resilience'. However, there is much debate about its precise meaning, allowing for much flexibility and uncertainties (e.g. Shaw and Maythorne 2013; Hassler and Kohler 2014; Jain et al. 2014). Contemporary resilience thinking is a new and rapidly emerging field in South Africa, and only eight percent of the evaluated publications included the concept of resilience (Table 4, Fig. 13). However, in 2013 resilience contributed to more than 50% of the total citation impact, indicating its current importance (Table 4, Fig. 13).

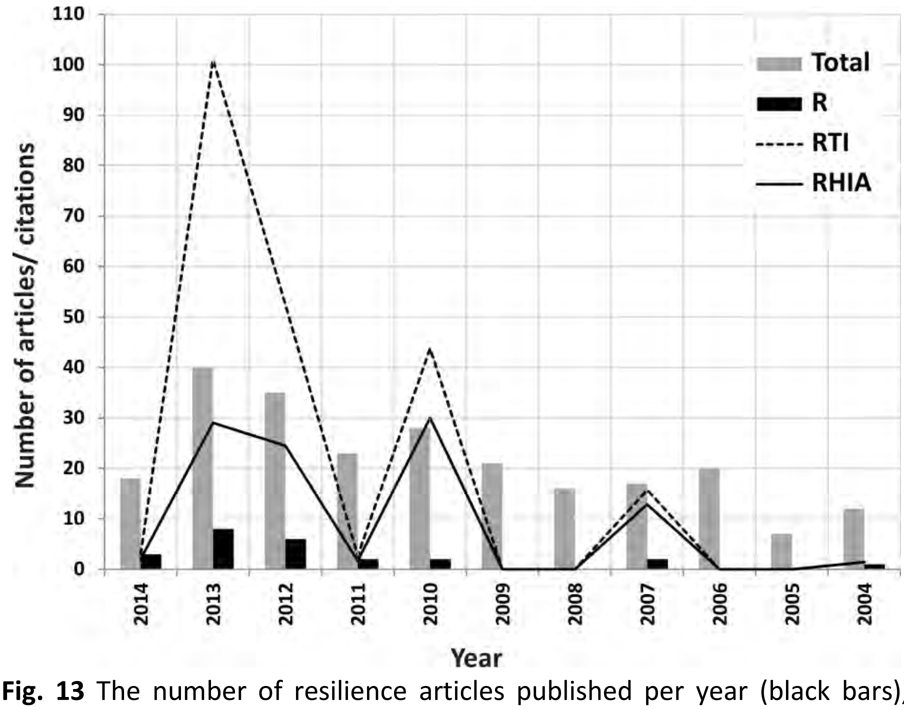

Fig. 13 The number of resilience articles published per year (black bars), indicating the total impact of the articles per year (RTI) and the highest impact article for each year (RHIA). Also shown are grey bars representing the total number of all articles per year.

Publications referring to the more familiar use of the term resilience in ecology meaning the "*ability of a living system to restore itself to its original condition after being disturbed*" (Lawrence 2005) were excluded in this discussion. Here the focus is on the more contemporary concepts of resilience in disaster-risk reduction, resilience of social-ecological systems, resilient cities, and building resilience to climate change.

Mgquba and Vogel (2004) discussed the vulnerability and importance of community resilience to disasters in urban environments. "*Social–ecological resilience is about people and nature as interdependent systems*" (Folke et al. 2010). Resilience thinking in terms of complex socio-ecological systems as explained by authors such as Folke (2006) and Carpenter et al. (2001) was applied by Le Maitre et al. (2007), Ernstson et al. (2010), Schäffler (2011), Ernstson (2013), McHale et al. (2013), Schäffler and Swilling (2013), and Cash (2014). The focus on urban resilience i.e. resilient cities was researched by Ernstson et al. (2010), Ernstson and Sörlin (2013), Wilkinson et al. (2013), and Ahern et al. (2014). However, the most publications referring to resilience are those on building resilience to climate change (e.g. Mukheibir and Ziervogel 2007; Roberts 2010; Carmin et al. 2012; Friedrich and Kretzinger 2012; Fatti and Patel 2013; Roberts and O'Donoghue 2013; Bulkeley et al. 2014). A testimony to the popularity and current significance of this theme is the fact that seven of the highest impact articles include resilience themes (Table 3). Additionally, number five in the top ten highest citations is the article by Ernstson et al. (2010) on urban resilience. This article also has the honour of being the highest impact article on urban ecological issues to date in South Africa (Table 3).

Future outlook

Some problems and challenges in South Africa

The management of nature in urban areas is often fraught with difficulties and clashes between conservation priorities and societal perceptions and interests. Examples include: fire management in Cape Town fynbos conservation areas—ecological goals versus societal fire suppression expectations in anxiety about infrastructure damage (van Wilgen et al. 2012); alien invasive tree removal in urban open space and dedicated urban conservation areas—utilized and appreciated by urban dwellers (van Wilgen 2012); the difficulties of managing feral cats in an urban conservancy—common sense, ethical issues and public sentiment do not allow for wholesale eradication (Tennent and Downs 2008; Tennent et al. 2009); broad societal expectations of neat well-kept formalistic appearances of open spaces in urban areas—such as mown grasslands and cleared open water courses despite potential detrimental ecological effects, 'wild nature' is perceived as poor municipal management (McDonnell 2007). Moreover, fear of criminal activities and urban wildlife such as spiders, snakes, rats and mice are often stated additional reasons for societal preferences.

Natural resources are often over-exploited and polluted in urban areas, due to a great demand on these resources, specifically for the upliftment of the urban poor (Le Maitre et al. 2007). Some of the major problems include the access to basic services, over-exploitation of water resources, pollution of ground- and surface-water resources, health impacts, and water leakage and wastage (Carden and Armitage 2013). Transformation and degradation of natural areas occur due to urbanization, e.g. pressure on public green spaces to be used for informal settlements, infrastructure development and urban agriculture (Shackleton and Blair 2013); impacts of informal settlements on vegetation, especially the collection of firewood (Berry et al. 1994; Banks et al. 1996); the destruction of wetlands (Lannas and Turpie 2009; Katz et al. 2014); conservation challenges in metropolitan Cape Town (Rebelo et al. 2011); and cultural influences on natural resources such as large scale harvesting of medicinal plants (Cocks and Dold 2006; Petersen et al. 2014).

Inequality regarding conservation and development goals are stark realities in South Africa as is clearly indicated by the following quotes: "*environmental issues are seen by many as a preoccupation of wealthy whites and anti-development groups*" (Le Maitre et al. 2007); "*the environment also suffers from a perception that it is a white, middle-class issue focused on nature conservation, that it is not relevant to the* *urgent needs of the country for development and social justice*” (Whyte 1995); “*the preservation of nature is regarded as fundamentally in opposition to socio-economic development. Conservation is frequently interpreted as being a socially unjust endeavor, disrespectful toward people and lacking realism*.” (Wilhelm-Rechmann and Cowling 2011); "*environmental concerns are regarded as being of less significance than development priorities in South Africa*"(Roberts 2008); and "*a recently urbanized person, living in a shack in an unplanned squalid area, might well perceive 'improvement of the environment' as provision of job opportunities, infrastructure and housing. In contrast, a more affluent person might consider that this infrastructure and housing is causing a deterioration of the environment, as yet another open space is built upon*" (Wall 1992).

Local authorities in South Africa have to keep up with increasing urbanization and its negative effect on resources and the resulting socio-economic pressures (Wall 1992; du Plessis et al. 2003; Carden and Armitage 2013) specifically in addressing backlogs in infrastructure provision (Parkin et al. 2006). Consequently, environmental issues, including aspects of urban forestry such as maintenance of street trees are neglected in budget allocations to address demands for housing and other infrastructure (Parkin et al. 2006; Kuruneri-Chitepo and Shackleton 2011). Municipal management strategies are also reactive rather than pro-active, e.g. in terms of the storm- and grey-water quality management strategies in informal settlements (Owusu-Asante and Ndiritu 2009). This is inseparably linked to a critical lack of capacity and technical skills in municipalities (Carden and Armitage 2013; Fatti and Patel 2013; Wilhelm-Rechmann and Cowling 2013). Lack of funding , the policy practice divide and the unmandated role of municipalities in biodiversity conservation implementation (Holmes et al. 2012) contribute to the inability of local governments to deal with future risks of climate change, even in some of our largest cities, such as Durban (Roberts 2010) and Cape Town (Pasquini et al. 2013). According to du Plessis et al. (2003) "*there is limited capacity (both human and financial) for modelling and predicting the future climate, as well as for actually implementing any suggested mitigation and adaptation initiatives. In general, it appears that South Africa is ill-prepared for the changes that climate change will bring, and is reluctant to take responsibility for its own role in the crisis and implement mitigation measures*" Municipal commonages are often mismanaged (Ingle 2006; Davenport et al. 2012). Moreover, local government planning practices do not deal effectively with competing land-uses such as indiscriminate development at the expense of green spaces (Cilliers 2009) and creating space for urban agriculture opportunities (Reuther and Dewar 2006). Development plans often include well versed environmental and sustainable commitments that do not survive the implementation phases, and many housing schemes do not include adequate urban green infrastructure (Shackleton et al. 2014). Moreover, many previously disadvantaged and poor areas have low vegetation cover, no established street trees or small public green spaces (McConnachie et al. 2008; McConnachie and Shackleton 2010; Kuruneri-Chitepo and Shackleton 2011; Schäffler and Swilling 2013).

Gaps in knowledge

The evaluation of the literature on the different themes identified important gaps:

- Physical environment: Comprehensive in-depth studies are lacking in the research on the physical environment. The bulk of the urban climate literature is old, and newer studies are needed covering more cities, as well as the effects of climate change developing dedicated adaptation plans. Despite all the literature on climate change, it only comprises 12% of all the publications evaluated. Soil is critically understudied, mostly as environmental variables in studies with another main focus. Studies on urban water bodies are almost exclusively on rivers. Pollution studies need attention, with most of them only focussing on Durban. Urban litter is almost exclusively studied by one research group and only focuses on the litter carried in water courses.

- Biodiversity: Literature revealed that 69% of biodiversity studies focused on vegetation. Second are birds comprising 16% of the studies, they and all the other biotic groups (mammals, amphibians, reptiles, fish, arthropods, algae, fungi and bacteria) need more attention. However, despite all the vegetation studies, gardens and urban forestry remain largely neglected. Also, there are too few biodiversity studies comparing patterns and processes of different settled areas in South Africa and abroad (Cilliers and Siebert 2012). More mechanistic approaches should also be followed, focusing less on the "*size, shape and location of remnant intact areas of biodiversity*" but more on "*those factors of the urban landscape that allow the persistence of species within a diverse matrix*" (Dures and Cumming 2010). Nonetheless, increasingly more studies focus on different biotic groups simultaneously.

- Management: Better incorporation is needed between science and policy; ecological research needs to be more real world problem solving and presented in formats more relevant to policymakers. The process of comanagement needs to be incorporated to manage natural resources and social relationships (Graham and Ernstson 2012).

- Conservation: Efforts need to be framed in relevant socially inclusive forms. Several studies indicated the importance of a community-based theme (including cultural and socio-economic issues) in the conservation of urban open spaces in South Africa (Ferketic et al. 2010; Graham and Ernstson 2012; Roberts et al. 2012) which is largely lacking. It is also important to include all relevant stakeholders in the conservation of natural resources (Le Maitre et al. 1997), including politicians (Wilhelm-Rechmann and Cowling 2013).

- Planning: Most of the planning studies are written from an ecological perspective; more planners are needed to incorporate the environment from a planning perspective. Overall, better collaboration is needed between planners and urban ecologists, following innovative approaches. More emphasis need to be put on green infrastructure planning in South African urban areas (Schäffler and Swilling 2013), and the so-called green value gap need to be addressed (Cilliers 2009).

- Human needs: This theme needs to be relativized, as it forms an important part of sustainable paradigms and cultural and social awareness and livelihood strategies.

- Sustainability: Specific goals need to be more focussed and clearly delineated. Expertise needs to be shared between cities.

- Public participation: Need to expand more formal interaction with the public. Better fine scale assessment tools and research on the embedded social values are needed (Ernstson and Sörlin 2013).

- Ecosystem services: Most of the research on ecosystem services are focusing on Durban and Cape Town and need to be expanded to other urban areas. According to Le Maitre et al. (2007) "*more direct interaction and development of an interdisciplinary understanding, common language and* *shared values between the different domains of science are required if the potential of research on ecosystem services for the understanding of complex, socio-ecological systems and to sustainable development are to be realized*."

- Resilience: In South Africa few researchers are focussing on resilience thinking. As this theme is increasingly globally acknowledged as a sensible way to study social-ecological systems, urban ecological research in South Africa need to investigate how it can be implemented in planning and management of urban areas (Ernstson et al. 2010; Roberts 2010; Schäffler and Swilling 2013).

General gaps in knowledge include insufficient research observation and short research time-spans (Putter 2004; Pantshwa 2006). From these data, clear trends cannot be identified, and informed decisions cannot be made. More long-term temporal studies are needed. There is also a general lack of comparable studies, e.g. municipal commonage usage (Davenport et al. 2011); limited literature on urban greening, and even less on urban forestry (Shackleton 2006; Kuruneri-Chitepo and Shackleton 2011); and few studies on urban green space areas in the developing world, especially in smaller towns (McConnachie et al. 2008).

Conclusion

Much emphasis is put on inter- and transdisciplinary themes in urban ecology literature (Kattel et al. 2013; Ahern et al. 2014; Childers et al. 2014; Cilliers et al. 2014; Wu 2014). Evaluation of the different themes followed in South African literature confirmed that urban ecology is indeed a highly interdisciplinary science. Only 41 (13%) of the studies researched only one theme, 50 (16%) incorporated two, 89 (28 %) three, 53 (17%) four, 50 (16%) five, 17 (5%) six, 7 (2%) seven, 3 (1%) eight, and 3 (1%) nine. Importantly, the themes of biodiversity and the physical environment are in themselves often interdisciplinary. The high number of articles incorporating public participation, albeit some only through questionnaires and surveys, is encouraging evidence for the advancement of more public involvement in real world problem solving. South African researchers have taken great strides in advancing the field locally as shown by the increase in the number of publications and citations to these publications over the years. Moreover, the global significance of South African contributions can also be seen in the inclusion of South African research in international publications. In physical environmental research, the work carried out in Johannesburg on urban heat islands was listed as an example of this phenomenon in a subtropical climate in a global review of urban climate research by Arnfield (2003). The metropolitan open space system of Durban was featured in a publication on urban wildlife ecology and conservation (Adams 2005). Furthermore, the research carried out in Johannesburg and especially Cape Town and Durban on climate change are internationally used examples (Sanchez-Rodriguez 2009; Anguelovski and Carmin 2011; Hunt and Watkiss 2011; Bulkeley and Betsill 2013; Castán Broto and Bulkeley 2013; Simon 2013). International planning themes include an article on urban common property systems in which a community driven urban green commons project in Cape Town is discussed as a case study (Colding et al. 2013). Potchefstroom, Ganyesa and Pretoria recently featured as part of a global analysis of 110 and 54 cities respectively comparing the impact of urbanization on plant and bird diversity patterns (Aronson et al. 2014). The same 110 cities, which included Ganyesa and Potchefstroom, were also used to determine the differences in beta diversity of urban vegetation between European and non-European cities (La Sorte et al. 2014). Additionally, Cape Town featured as a case study on conflicts arising from the management of invasive trees (Dickie et al. 2013).

Accounting for the problems and addressing the identified gaps in future research will enhance our understanding and broaden our knowledge. Furthermore, we hope that this overview will encourage researchers to effectively incorporate information from this collection of publications into future research efforts. This could rapidly increase progress in the field and ensure the sustained relevance and quality of our research towards enhancing environmental integrity in urban areas and sustainable solutions.

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Supplementary Tables 1- 4: The 314 evaluated publications listed in chronological order. Each publication shows the following: international authorship (INT) (N - no, Y - some of the authors non-South Africans, YY - all authors non-South Africans); the location of the study; the provincial location (Prov) (GP - Gauteng, KZN - KwaZulu-Natal, WC - Western Cape, EC - Eastern Cape, NC - Northern Cape, NW - North-West, L - Limpopo, MP - Mpumalanga, FS - Free State); publication date (date); the number of years since publication (YRS); the number of citations as on 27 August 2014 in Google Scholar (cit 08/27); the citation impact (impact) (the amount of citations divided by the years since publication). The research themes are indicated by: **Public participation (PP):** CE - Civic ecology, CJ - Conservation justice, CS - Civic science, EJ - Environmental justice, PE - Political ecology, SQI - surveys/questionnaires/ interviews; **Human needs (HN):** A - Urban agriculture, M - Medicinal plants, TF - Trees and fire/fuel wood; **Ecosystem services (ES); Management (M):** MC - Municipal commonage; **Conservation (C); Physical environment (PE):** A - Air, C - Climate, CG - Climate change, D - Disasters, P - Pollution, S - Soil, W - Water, WB - Water bodies; **Planning (PL); Biodiversity (B):** A - Amphibians, AL - Algae, BC - Bacteria, BI - Birds, F - Fish, FG - Fungi, I - Invertebrates, M - Mammals, R - Reptiles, V - Vegetation; **Sustainability (S); Resilience (R).**

ST 1: 1965-1999

Reference	INT	Location	Prov	date	YRS	cit 09/27	impact	PP	HN	ES	M	C	PE	PL	B	S	R
Louw and Meyer (1965)	N	Pretoria	GP	1965	49	7	0.14						PE (C)				
Tyson (1968)	N	Pietermaritzburg	KZN	1968	46	45	0.98						PE (C)				
Goldreich (1970)	YY	Johannesburg	GP	1970	44	16	0.36						PE (C)				
Goldreich (1971)	YY	Johannesburg	GP	1971	43	9	0.21						PE (C)				
Venter (1971)	N	Richard’s Bay	KZN	1971	43	0	0.00						PE (WB)		B(V)		
Tyson et al. (1972)	N	Johannesburg, Durban, Pietermaritzburg	GP, KZN	1972	42	33	0.79						PE (C)				
Tyson and Von Gogh (1976)	N	Johannesburg	GP	1976	38	7	0.18						PE (C)				
Goldreich (1979)	YY	Johannesburg	GP	1979	35	6	0.17						PE (C)				
von Gogh (1979)	N	Pretoria	GP	1979	35	5	0.14						PE (C)				
Morkel (1980)	N	Pretoria	GP	1980	34	2	0.06						PE (C)				
Tyson et al. (1980)	Y	Johannesburg, Pretoria	GP	1980	34	5	0.15						PE (C)				
Ward (1980)	N	Isipingo Beach	KZN	1980	34	11	0.32		HN (M)						B(V) (M) (I) (BI) (FG)		
Goldreich et al. (1981b)	N	Johannesburg	GP	1981	33	12	0.36						PE (C)				
Goldreich et al. (1981a)	Y	Johannesburg	GP	1981	33	7	0.21						PE (C)				

Goldreich (1985)	YY	Johannesburg	GP	1985	29	54	1.86						PE (C)				
Poynton and Roberts (1985)	N	Cape Town, Johannesburg, Durban	WC, GP, KZN	1985	29	11	0.38				M	C		PL			
Goldreich and Surridge (1988)	N	Johannesburg	GP	1988	26	13	0.50						PE (C)				
Surridge and Goldreich (1988)	N	Johannesburg	GP	1988	26	2	0.08						PE (C)				
Dauskardt (1990)	N	Johannesburg, Randfontein, Krugersdorp, Roodepoort, Soweto, Sandton, Alexandra, Alberton, Kempton park, Boksburg, Benoni, Brakpan, Springs	GP	1990	24	34	1.42		HN (M)								
Wood and Samways (1991)	N	Pietermaritzburg	KZN	1991	23	66	2.87				M	C			B(I)		
Goldreich (1992)	YY	Johannesburg	GP	1992	22	26	1.18						PE (C)				
Wall (1992)	N	No specific		1992	22	NF	N/A				M	C		PL			
Roberts (1993)	N	Durban	KZN	1993	21	8	0.38						PE (S) (WB)		B(V)		
Rogerson (1993a)	N	No specific		1993	21	59	2.81		HN (A)								
Rogerson (1993b)	N	No specific		1993	21	43	2.05		HN (A)		M			PL		S	
Berry et al. (1994)	N	Port Alfred, Kenton-on-Sea, Jeffrey's Bay, Plettenberg Bay, Knysna	EC	1994	20	8	0.40		HN (TF) (M)			C			B(V)		
May and Rogerson (1995)	N	Groutville, Tembisa (Johannesburg), Umtata	KZN, GP, EC	1995	19	78	4.11	PP (SQI)	HN (A)		M			PL		S	
Steytler and Samways (1995)	N	Pietermaritzburg	KZN	1995	19	59	3.11				M	C	PE (WB)		B(I)		

Wisner (1995)	YY	Alexandra (Johannesburg)	GP	1995	19	6	0.32	PP (EJ) (SQI)			M		PE (D) (AP) (WP) (SP)				
Wisner and Luce (1995)	YY	Alexandra (Johannesburg)	GP	1995	19	42	2.21	PP (SQI)			M		PE (D)	PL		S	
Banks et al. (1996)	N	Athol, Welverdiend	MP	1996	18	64	3.56	PP (SQI)	HN (TF)							S	
Samways and Steytler (1996)	N	Pietermaritzburg	KZN	1996	18	128	7.11				M	C	PE (WB)		B (I) (V)		
Clark and Samways (1997)	N	Pietermaritzburg	KZN	1997	17	30	1.76				M	C			B (I) (V)		
Le Maitre et al. (1997)	Y	Cape Town	WC	1997	17	13	0.76	PP (SQI)	HN			C				S	
McDonald (1997)	YY	Cape Town	WC	1997	17	8	0.47	PP (EJ) (SQI)			M	C	PE (AP) (WP) (SP)				
McGeoch and Chown (1997)	N	Pretoria	GP	1997	17	48	2.82					C			B (I) (V)		
van Wyk et al. (1997)	N	Klerksdorp	NW	1997	17	0	0.00					C	PE (S)		B(V)		
Williams et al. (1997)	N	Alberton, Bedfordview, Benoni, Boksburg, Brakpan, Edenvale, Germiston, Kempton Park, Nigel, Springs, Johannesburg, Midrand, Randburg, Sandton, Krugersdorp, Randfontein, Roodepoort, Westonaria.	GP	1997	17	18	1.06	PP	HN (M)						B(V)		
Cilliers and Bredenkamp (1998)	N	Potchefstroom	NW	1998	16	11	0.69						PE (S)		B(V)		
Cilliers et al. (1998)	N	Potchefstroom	NW	1998	16	12	0.75					C	PE (S) (WB)		B(V)		

McDonald (1998)	YY	No specific		1998	16	24	1.50	PP (EJ) (PE)			M	C				S	
Rogerson (1998)	N	No specific		1998	16	21	1.31	PP (SQI)	HN (A)					PL		S	
Armitage and Rooseboom (1999)	N	No specific		1999	15	16	1.07				M		PE (WP)				
Cilliers and Bredenkamp (1999b)	N	Potchefstroom	NW	1999	15	NF	N/A						PE (S)		B(V)		
Cilliers and Bredenkamp (1999a)	N	Potchefstroom	NW	1999	15	13	0.87				M		PE (S)		B(V)		
Cilliers et al. (1999)	N	Potchefstroom	NW	1999	15	13	0.87		HN (TF)			C	PE (S)		B(V)		

ST 2: 2000-2005

Reference	INT	Location	Prov	date	YRS	cit 09/27	impact	PP	HN	ES	M	C	PE	PL	B	S	R
Armitage and Rooseboom (2000a)	N	Springs, Johannesburg, Cape Town	GP, WC	2000	14	51	3.64				M		PE (WP) (WB)				
Armitage and Rooseboom (2000b)	N	No specific		2000	14	17	1.21				M		PE (WP)				
Cilliers and Bredenkamp (2000)	N	Potchefstroom	NW	2000	14	50	3.57						PE (S)		B(V)		
Dold and Cocks (2000a)	N	Grahamstown, Peddie	EC	2000	14	18	1.29	PP (SQI)	HN (M)						B(V)		
Dold and Cocks (2000b)	N	Nomtayi, Ripplemead, Tweni, Ndwayana, Glenmore, Gwabeni	EC	2000	14	8	0.57	PP (SQI)	HN (TF) (M)						B(V)		
Oelofse and Patel (2000)	Y	Clermont (Durban)	KZN	2000	14	11	0.79	PP			M	C		PL		S	
Rösner and Van Schalkwyk (2000)	Y	Johannesburg	GP	2000	14	27	1.93						PE (SP)				
Van Wyk et al. (2000)	N	Klerksdorp	NW	2000	14	13	0.93						PE (S) (WB)		B(V)		

Williams et al. (2000)	N	Alberton, Bedfordview, Benoni, Boksburg, Brakpan, Edenvale, Germiston, Kempton Park, Nigel, Springs, Johannesburg, Midrand, Randburg, Sandton, Krugersdorp, Randfontein, Roodepoort, Westonaria.	GP	2000	14	116	8.29	PP (SQI)	HN (M)						B(V)		
Freund (2001)	N	Durban	KZN	2001	13	34	2.62	PP (SQI)			M	C		PL		S	
Grobicki (2001)	N	Cape Town	WC	2001	13	13	1.00	PP			M		PE (W) (WB)				
Matsiliza and Barker (2001)	N	Grahamstown	EC	2001	13	14	1.08	PP (SQI)	HN (M)			C			B(V)		
Morrison et al. (2001)	Y	King Williams Town	EC	2001	13	19	1.46				M		PE (W) (WB)			S	
Slater (2001)	YY	Cape Town	WC	2001	13	57	4.38	PP (SQI)	HN (A)								
Dold and Cocks (2002)	N	Port Elizabeth, Uitenhage, East London, King William’s Town, Umtata, Queenstown	EC	2002	12	162	13.50	PP (SQI)	HN (M)			C			B(V)	S	
Faber et al. (2002)	N	Ndunakazi	KZN	2002	12	85	7.08	PP (SQI)	HN (A)						B(V)		
Fatoki et al. (2002)	Y	Umtata, Tabase, Kanbi	EC	2002	12	59	4.92						PE (WP) (WB)				

Grobler et al. (2002)	N	Pretoria, Midrand, Johannesburg, West Rand	GP	2002	12	17	1.42					C	PE (S)		B(V)		
McGeoch (2002)	N	No specific		2002	12	24	2.00					C			B(I)	S	
Roberts and Diederichs (2002)	N	Durban	KZN	2002	12	20	1.67	PP (SQI)			M		PE (CG)	PL		S	
Saayman and Adams (2002)	N	Cape Town	WC	2002	12	7	0.58				M		PE (W)				
Scott et al. (2002)	N	Durban	KZN	2002	12	10	0.83	PP (EJ)					PE (AP)				
Whitmore et al. (2002)	N	Durban	KZN	2002	12	16	1.33				M	C			B(I)		
Ackerman and Talbot (2003)	Y	Cape Town	WC	2003	11	1	0.09	PP			M				B(V)		
Cocks and Wiersum (2003)	Y	Woodlands (near Peddie)	EC	2003	11	81	7.36	PP (SQI)	HN (TF) (M) (A)			C			B(V)		
du Plessis et al. (2003)	N	No specific		2003	11	30	2.73	PP	HN (TF)		M		PE (CG)			S	
Naicker et al. (2003)	N	Johannesburg	GP	2003	11	123	11.18						PE (WP) (SP)				
Roberts (2003)	N	Durban	KZN	2003	11	5	0.45	PP (SQI)			M			PL		S	
Rogerson (2003b)	N	No specific		2003	11	27	2.45		HN (A)		M			PL		S	
Rogerson (2003a)	N	Midrand (Johannesburg)	GP	2003	11	9	0.82	PP (SQI)	HN (A)		M			PL		S	
Schwarzenberger and Dean (2003)	Y	Prince Albert	WC	2003	11	1	0.09	PP							B (BI) (V)		
Botha et al. (2004)	Y	Thohoyandou, Sibasa, Giyani, Malamulele, Louis Trichardt, Phalaborwa, Hazyview, Nelspruit	L, MP	2004	10	14	1.40	PP (SQI)	HN (M)		M	C					
Cilliers et al. (2004)	Y	Potchefstroom, Klerksdorp	NW	2004	10	34	3.40				M	C		PL	B(V)	S	

Debbané and Keil (2004)	YY	Hermanus	WC	2004	10	49	4.90	PP (EJ)			M	C	PE (W)			S	
Drewes and Cilliers (2004)	N	Potchefstroom	NW	2004	10	6	0.60					C		PL		S	
Marais and Armitage (2004)	N	Cape Town	WC	2004	10	12	1.20	PP			M		PE (WP)	PL		S	
Marais et al. (2004)	N	Cape Town	WC	2004	10	9	0.90				M		PE (WP)				
Mgquba and Vogel (2004)	N	Alexandra (Johannesburg)	GP	2004	10	14	1.40	PP (SQI)			M		PE (WB) (D) (CG)				R
Pieterse (2004)	N	No specific		2004	10	28	2.80				M			PL		S	
Putter (2004)	N	Potchefstroom	NW	2004	10	1	0.10				M	C	PE (S)	PL	B(V)	S	
Shackleton and Shackleton (2004)	N	King William's Town, Bushbuckridge	EC, MP	2004	10	247	24.70	PP (SQI)	HN (TF) (M) (A)						B(V)	S	
Smith (2004)	N	Potchefstroom	NW	2004	10	2	0.20					C			B (BI)	S	
Todes (2004)	N	Ugu District Municipality	KZN	2004	10	17	1.70	PP (SQI)				C		PL		S	
Kaschula et al. (2005)	N	Welverdiend	MP	2005	9	37	4.11	PP (SQI)	HN (TF)		M	C			B(V)	S	
Odiyo et al. (2005)	N	Thohoyandou	L	2005	9	21	2.33						PE (SP) (WP) (WB)				
Okonkwo and Mothiba (2005)	N	Thohoyandou	L	2005	9	34	3.78						PE (WP) (WB)				
Patel (2005)	N	No specific		2005	9	5	0.56				M			PL		S	
Roberts et al. (2005)	N	Durban	KZN	2005	9	6	0.67	PP		ES	M	C		PL		S	
Scott and Oelofse (2005)	N	Durban	KZN	2005	9	35	3.89	PP (EJ)			M		PE (SP)	PL		S	
Williams et al. (2005)	N	Johannesburg	GP	2005	9	40	4.44	PP (SQI)	HN (M)								

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Reference	INT	Location	Prov	date	YRS	cit 09/27	impact	PP	HN	ES	M	C	PE	PL	B	S	R
Alston and Richardson (2006)	N	Cape Town	WC	2006	8	97	12.13				M	C	PE (S)		B(V)		
Boraine et al. (2006)	N	No specific		2006	8	70	8.75				M					S	
Cocks and Dold (2006)	N	King Williams Town, East London	EC	2006	8	32	4.00	PP (SQI)	HN (M)			C					
Goldreich (2006)	YY	Johannesburg	GP	2006	8	22	2.75						PE (C)				
Grobler et al. (2006)	N	Pretoria, Midrand, Johannesburg, West Rand	GP	2006	8	20	2.50					C	PE (S)		B(V)		
Ingle (2006)	N	No specific		2006	8	14	1.75				M (MC)			PL			
Kruger (2006)	N	Clairwood (Durban)	KZN	2006	8	0	0.00	PP (SQI)			M	C	PE (AP)	PL		S	
Nel (2006)	N	Potchefstroom	NW	2006	8	0	0.00	PP (SQI)			M		PE (AP) (CG)			S	
Okonkwo et al. (2006)	Y	Tshwane Metropolitan Area	GP	2006	8	9	1.13						PE (SP)				
Pantshwa (2006)	N	Potchefstroom	NW	2006	8	NF	N/A				M		PE (WP) (WB)		B (BC)	S	
Parkin et al. (2006)	N	Grahamstown	EC	2006	8	4	0.50	PP (SQI)	HN (TF) (M)						B(V)		
Pelser (2006)	N	Potchefstroom	NW	2006	8	0	0.00			ES			PE (S)		B(V)		
Reuther and Dewar (2006)	N	Khayelitsha (Cape Town)	WC	2006	8	20	2.50	PP	HN (A)					PL	B(V)		
Shackleton (2006)	N	No specific		2006	8	10	1.25				M				B(V)		
Shackleton et al. (2006)	N	Grahamstown	EC	2006	8	13	1.63	PP (SQI)	HN (TF)						B(V)		
Swilling (2006)	N	Cape Town	WC	2006	8	44	5.50	PP (SQI)			M		PE	PL		S	

Swilling and Annecke (2006)	N	Stellenbosch	WC	2006	8	21	2.63	PP			M		PE	PL		S	
Van Eeden (2006)	N	Carletonville	NW	2006	8	3	0.38	PP (SQI)			M		PE (WP) (D) (WB)				
Whittington et al. (2006)	N	Port Elizabeth	EC	2006	8	5	0.63								B (BI)		
Zobolo and Mkabela (2006)	N	Mbonambi, Umhlathuze (Dlangezwa), Ntambanana and Umlalazi (Eshowe) [Uthungulu District Municipality]	KZN	2006	8	20	2.50	PP (SQI)	HN (A) (M)						B(V)		
Armitage (2007)	N	Cape Town	WC	2007	7	4	0.57	PP (SQI)			M		PE (WP)	PL			
Barnett and Scott (2007b)	Y	Durban	KZN	2007	7	35	5.00	PP (EJ)			M		PE (AP)				
Barnett and Scott (2007a)	Y	Durban	KZN	2007	7	11	1.57	PP (CS)			M		PE (AP)			S	
Diab and Motha (2007)	N	Durban	KZN	2007	7	6	0.86	PP			M		PE (AP)				
Donaldson-Selby et al. (2007)	N	Durban	KZN	2007	7	8	1.14	PP (SQI)				C		PL	B(V)	S	
García-Rodríguez et al. (2007)	N	Port Elizabeth	EC	2007	7	3	0.43				M		PE (WP) (WB)		B (AL)		
Goebel (2007)	YY	Pietermaritzburg (Msunduzi Municipality)	KZN	2007	7	46	6.57	PP (EJ) (SQI)			M					S	
Holgate (2007)	Y	Cape Town, Johannesburg	WC, GP	2007	7	54	7.71	PP (SQI)			M		PE (CG)			S	
Jonas (2007)	N	Potchefstroom	NW	2007	7	0	0.00						PE (S)		B (I) (V)		
Law (2007)	N	East London	EC	2007	7	3	0.43	PP (SQI)		ES	M	C	PE (WB)		B(V)	S	
Le Maitre et al. (2007)	N	No specific		2007	7	20	2.86			ES						S	R

Madubansi and Shackleton (2007)	N	Athol, Okkerneutboom, Rolle, Welverdiend, Xanthia	MP	2007	7	68	9.71	PP (SQI)	HN (TF)						B(V)		
Mukheibir and Ziervogel (2007)	N	Cape Town	WC	2007	7	90	12.86				M		PE (D) (W) (CG)	PL		S	R
Thornton and Nel (2007)	Y	Peddie	EC	2007	7	12	1.71	PP (SQI)	HN (A)								
van Averbeke (2007)	N	Atteridgeville (Pretoria)	GP	2007	7	24	3.43	PP (SQI)	HN (A)								
Van der Walt et al. (2007)	N	Phokeng	NW	2007	7	1	0.14		HN (A)				PE (S)		B (FG) (V)		
Wilken (2007)	N	Nelspruit, Hazyview [Mbombela Local Municipality]	MP	2007	7	1	0.14		HN (TF) (M)	ES	M	C	PE (S) (WB)	PL	B(BI) (V)	S	
Batterman et al. (2008)	Y	Durban	KZN	2008	6	29	4.83						PE (AP)				
Burger (2008)	N	Richards Bay	KZN	2008	6	1	0.17				M	C	PE (WB)		B(V)		
Cilliers et al. (2008)	Y	Potchefstroom	NW	2008	6	23	3.83					C			B(V)		
Faul (2008)	YY	Cape Town	WC	2008	6	4	0.67	PP (SQI)				C					
Forsyth and van Wilgen (2008)	N	Cape Town	WC	2008	6	38	6.33				M	C			B(V)		
Makunga et al. (2008)	N	No specific		2008	6	34	5.67		HN (M)			C			B(V)	S	

McConnachie et al. (2008)	N	Mosselbay, Graaff-Reinet, Fort Beaufort, Grahamstown, Jeffrey's Bay, Port Elizabeth, Zwelitsha, King Williams Town, Bisho, Butterworth	WC, EC	2008	6	31	5.17							PL	B(V)		
Phiri (2008)	N	Mdantsane, Duncan Village, Potsdam [Buffalo City Municipality]	EC	2008	6	3	0.50	PP (SQI)	HN (A)						B (V) (M) (BI)	S	
Roberts (2008)	N	Durban	KZN	2008	6	114	19.00				M		PE (CG)	PL	B	S	
Stoffberg et al. (2008)	N	Pretoria (City of Tswane)	GP	2008	6	16	2.67								B(V)		
Sutton (2008)	YY	Pietermaritzburg (Msunduzi Municipality)	KZN	2008	6	2	0.33	PP (SQI)			M	C	PE (WP) (WB)	PL	B	S	
Tennent and Downs (2008)	N	Durban	KZN	2008	6	8	1.33				M	C			B(M)		
Thornton (2008)	YY	Grahamstown, Peddie	EC	2008	6	47	7.83	PP (SQI)	HN (A)						B(M) (BI)	S	
Van Eeden (2008)	N	Merafong City Municipality	GP	2008	6	7	1.17	PP (SQI)			M	C	PE (W) (D) (WP) (WB)				
Van Wyk et al. (2008)	N	Graaff-Reinet, Murraysburg	WC, EC	2008	6	38	6.33	PP (SQI)	HN (M)						B(V)		
Ziervogel and Taylor (2008)	Y	Mohlotsi, Ga-Selala (Marble Hall and Greater Tubatse municipalities)	L	2008	6	39	6.50	PP (SQI)			M		PE (CG)			S	
Batterman et al. (2009)	Y	Durban	KZN	2009	5	32	6.40						PE (AP) (SP)				

Cilliers (2009)	N	No specific		2009	5	NF	N/A				M			PL		S	
Cilliers et al. (2009)	N	No specific		2009	5	10	2.00		HN (A)		M			PL	B	S	
Davoren (2009)	N	Ganyesa	NW	2009	5	1	0.20	PP (SQI)	HN (A) (M)			C			B(V)	S	
du Toit (2009)	N	Klerksdorp, Orkney	NW	2009	5	2	0.40					C	PE (S)		B(V)		
Lannas and Turpie (2009)	N	Cape Town	WC	2009	5	11	2.20	PP (SQI)	HN (TF) (M)	ES			PE (WB)		B (V) (M) (BI)	S	
Marchand et al. (2009)	N	Rietvlei Nature Reserve (Pretoria)	GP	2009	5	29	5.80						PE (WP) (SP) (WB)		B(F)		
Materechera (2009)	N	Mafikeng	NW	2009	5	9	1.80		HN (A)		M		PE (S)				
Owusu-Asante and Ndiritu (2009)	N	Alexandra (Johannesburg)	GP	2009	5	3	0.60	PP (SQI)			M		PE (W) (WB)			S	
Pryke and Samways (2009)	N	Cape Town	WC	2009	5	32	6.40				M	C			B (I) (V)		
Scott and Barnett (2009)	Y	Durban	KZN	2009	5	33	6.60	PP (CS)			M		PE (AP)			S	
Tennent et al. (2009)	N	Durban	KZN	2009	5	3	0.60				M	C			B(M)		
Thornton (2009)	YY	Peddie	EC	2009	5	23	4.60	PP (SQI)	HN (A)		M (MC)			PL		S	
van Dyk et al. (2009)	N	Pretoria	GP	2009	5	13	2.60						PE (WP) (SP) (WB)		B(F)		
van Huyssteen et al. (2009)	N	No specific		2009	5	11	2.20				M			PL			
van Rensburg et al. (2009)	N	Pretoria	GP	2009	5	26	5.20								B (BI)		
van Rooyen (2009)	N	Austrey, Mmagabue, Southey	NW	2009	5	0	0.00					C			B (BI) (V)	S	

Walsh and Wepener (2009)	N	Urban sites above and below Hartbeespoort Dam	NW, GP	2009	5	14	2.80						PE (W) (WB)		B (AL)		
Watson (2009)	N	No specific		2009	5	99	19.80				M			PL		S	
Whiting et al. (2009)	Y	7 villages in the Bushbuckridge Local Municipality	MP	2009	5	0	0.00	PP (SQI)	HN (TF)						B (R) (V)		
Wilson et al. (2009)	Y	Cape Metropolitan Area	WC	2009	5	16	3.20						PE (AP)		B (V)		
Aylett (2010a)	YY	Durban	KZN	2010	4	38	9.50	PP (EJ) (SQI)			M		PE (AP) (CG)	PL		S	
Aylett (2010b)	YY	Durban	KZN	2010	4	27	6.75	PP (EJ) (SQI)			M		PE (CG)	PL		S	
Brooks et al. (2010)	N	Durban	KZN	2010	4	2	0.50	PP (SQI)			M		PE (AP) (WP)				
Cilliers (2010)	N	Potchefstroom, Cape Town, Durban	NW, WC, KZN	2010	4	15	3.75	PP	HN (A)			C		PL	B	S	
Cilliers and Drewes (2010)	N	Tlokwe Local Municipality	NW	2010	4	1	0.25				M	C		PL	B	S	
Daemane et al. (2010)	N	Potchefstroom	NW	2010	4	3	0.75					C	PE (S)		B(V)		
Dures and Cumming (2010)	N	Cape Town	WC	2010	4	14	3.50					C			B (BI)		
Ernstson et al. (2010)	Y	Cape Town	WC	2010	4	120	30.00	PP (CE)		ES	M	C	PE (W) (CG)	PL	B	S	R
Faber et al. (2010)	N	Not specified	L, KZN	2010	4	19	4.75	PP (SQI)	HN (A)						B(V)	S	
Ferketic et al. (2010)	YY	Cape Town	WC	2010	4	9	2.25	PP (CJ)			M	C		PL		S	
Goebel et al. (2010)	Y	Pietermaritzburg	KZN	2010	4	5	1.25	PP								S	

Jansen van Rensburg (2010)	N	Potchefstroom	NW	2010	4	NF	N/A						PE (S)		B (FG) (BC) (V)		
Leonard and Pelling (2010)	YY	Durban	KZN	2010	4	10	2.50	PP (EJ)					PE (SP) (AP) (WP)				
Lubbe et al. (2010)	N	Potchefstroom	NW	2010	4	32	8.00	PP	HN (A) (M)						B(V)		
McConnachie and Shackleton (2010)	N	Mosselbay, Graaff-Reinet, Fort Beaufort, Grahamstown, Jeffrey's Bay, Port Elizabeth, Zwelitsha, King Williams Town, Butterworth	WC, EC	2010	4	29	7.25							PL			
Meek et al. (2010)	N	Stellenbosch	WC	2010	4	26	6.50			ES	M	C	PE (S) (WB)		B(V)		
Molebatsi et al. (2010)	N	Tlhakgameng, Ganyesa, Ikageng (Potchefstroom)	NW	2010	4	11	2.75	PP	HN (A) (M)						B(V)		
Olowoyo et al. (2010)	N	Tshwane	GP	2010	4	14	3.50						PE (AP) (SP)		B(V)		
Pieterse et al. (2010)	N	Tshwane	GP	2010	4	6	1.50						PE (WP) (SP) (WB)		B(F)		
Pietersen et al. (2010)	N	Pretoria	GP	2010	4	1	0.25								B (BI)		
Roberts (2010)	N	Durban	KZN	2010	4	55	13.75				M		PE (D) (CG)	PL	B	S	R
Ross et al. (2010)	N	Johannesburg, Durban, Stellenbosch, Kimberley, Rustenburg	GP, KZN, WC, NC, NW	2010	4	5	1.25	PP (SQI)			M			PL		S	

Shackleton et al. (2010)	Y	Durban	KZN	2010	4	8	2.00	PP (SQI)	HN (A)						B(V)		
Stoffberg et al. (2010)	N	City of Tshwane Metropolitan Municipality	GP	2010	4	33	8.25			ES					B(V)		
Swilling (2010)	N	Cape Town	WC	2010	4	NF	N/A	PP	HN (A)		M	C	PE (W) (WP) (SP)	PL		S	
Ward et al. (2010)	N	Betty's Bay, Cape Town, Worcester, Bloemfontein, Johannesburg, Pretoria	GP, WC, FS	2010	4	23	5.75	PP (SQI)				C			B		
Ziervogel et al. (2010a)	Y	Cape Town	WC	2010	4	24	6.00	PP (SQI)			M		PE (W) (CG)				
Ziervogel et al. (2010b)	Y	Cape Town	WC	2010	4	19	4.75	PP (SQI)			M		PE (W) (CG)	PL			

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Reference	INT	Location	Prov	date	YRS	cit 09/27	impact	PP	HN	ES	M	C	PE	PL	B	S	R
Philander et al. (2011)	Y	Cape Town	WC	2011	3	7	2.33	PP (SQI)	HN (M)			C			B(V)	S	
Ballard and Jones (2011)	Y	Durban	KZN	2011	3	15	5.00	PP (SQI)				C		PL	B (V) (M) (BI) (I)		
Cilliers and Siebert (2011)	N	No specific		2011	3	10	3.33				M	C			B(V)	S	
Cilliers et al. (2011a)	N	Potchefstroom, Ganyesa	NW	2011	3	11	3.67	PP (SQI)	HN (A) (M)		M	C			B(V)		
Cilliers et al. (2011b)	N	Klerksdorp, Durban, Cape Town	NW, KZN, WC	2011	3	2	0.67	PP			M	C		PL		S	

Davenport et al. (2011)	N	Bathurst, Fort Beaufort, Grahamstown	EC	2011	3	10	3.33	PP (SQI)	HN (TF) (M)		M (MC)				B	S	
du Toit and Cilliers (2011)	N	Klerksdorp	NW	2011	3	14	4.67										
Fatti and Vogel (2011)	N	Johannesburg	GP	2011	3	5	1.67				M		PE (C) (D) (CG)			S	R
Hoffman and O'Riain (2011)	N	Tokai (Cape Town)	WC	2011	3	17	5.67				M		PE (C)		B(M) (V)		
Kimemia and Annegarn (2011)	N	Alexandra (Johannesburg)	GP	2011	3	5	1.67	PP (SQI)	HN (TF)						B(V)		
Kuruneri-Chitepo and Shackleton (2011)	N	Port Alfred, Grahamstown, Somerset East	EC	2011	3	14	4.67	PP (SQI)						PL	B(V)		
Leonard (2011)	N	Durban	KZN	2011	3	5	1.67	PP (EJ)					PE (SP) (AP) (WP)				
Lubbe et al. (2011)	N	Potchefstroom	NW	2011	3	4	1.33	PP	HN (A) (M)			C			B(V)		
Materechera (2011)	N	Mafikeng	NW	2011	3	1	0.33		HN (A)		M		PE (S)				
Naidoo et al. (2011)	N	Pretoria, Magaliesberg mountain range	GP, NW	2011	3	3	1.00	PP				C			B (BI)		
Nieuwoudt et al. (2011)	Y	Vanderbijlpark, Sasolburg, Vereeniging, Douglas	GP, FS, NC	2011	3	11	3.67						PE (SP)				

O'Farrell et al. (2011)	N	21 Magisterial districts: Calitzdorp, Calvinia, Ceres, Clanwilliam, George, Ladismith, Laingsburg, Montagu, Namakwaland, Oudtshoorn, Prince, Riversdal, Robertson, Steytlerville, Sutherland, Swellendam, Uniondale, Vanrhynsdorp, Vredendal, Willowmore, Worcester.	NC, WC, EC	2011	3	15	5.00	PP (SQI)		ES	M	C				S	
Pryke et al. (2011)	N	Cape Town	WC	2011	3	2	0.67					C			B (BI) (I) (V)		
Rebelo et al. (2011)	N	Cape Town	WC	2011	3	30	10.00				M	C		PL	B (V) (M) (BI) (R) (A) (F)		
Rogerson (2011)	N	Metropolitan Municipalities of Ekurhuleni, Tshwane, Johannesburg	GP	2011	3	7	2.33	PP	HN (A)		M			PL		S	
Schäffler (2011)	N	Johannesburg	GP	2011	3	3	1.00	PP (SQI)		ES	M	C	PE (CG)	PL	B(V)	S	R
Webb (2011)	N	No specific		2011	3	9	3.00		HN (A)							S	
Wilhelm-Rechmann and Cowling (2011)	N	4 Eastern Cape coastal local municipalities	EC	2011	3	9	3.00	PP (SQI)				C		PL		S	
Anderson and Elmqvist (2012)	Y	Cape Town	WC	2012	2	7	3.50				M	C		PL		S	R

Anderson and O'Farrell (2012)	N	Cape Town	WC	2012	2	10	5.00			ES	M	C				S	R
Botha (2012)	N	Potchefstroom	NW	2012	2	0	0.00	PP (SQI)	HN (A)		M	C	PE (S)		B(I) (V)	S	
Carmin et al. (2012)	Y	Durban	KZN	2012	2	49	24.50	PP (SQI)			M		PE (CG)	PL		S	R
Cilliers and Siebert (2012)	N	Cape Town, Durban	WC	2012	2	5	2.50			ES	M	C		PL	B	S	
Daemane et al. (2012)	N	Potchefstroom	NW	2012	2	0	0.00					C	PE (S)		B(V)		
Davenport et al. (2012)	N	Bathurst, Fort Beaufort, Grahamstown	EC	2012	2	11	5.50	PP (SQI)	HN (TF) (M)	ES	M (MC)				B(M) (V)	S	
de Wit et al. (2012)	N	Cape Town	WC	2012	2	5	2.50	PP (SQI)		ES	M						
Faling et al. (2012)	N	George Local Municipality, //Khara Hais Local Municipality	NC, WC	2012	2	9	4.50	PP (SQI)			M		PE (D) (CG)	PL		S	
Friedrich and Kretzinger (2012)	N	eThekwini Municipality	KZN	2012	2	1	0.50	PP (SQI)			M		PE (D) (CG)				R
Geerts and Pauw (2012)	N	Cape St. Francis, Port Elizabeth	EC	2012	2	3	1.50					C			B (BI) (V) (I)		
Graham and Ernstson (2012)	Y	Cape Town	WC	2012	2	6	3.00	PP (SQI)			M	C		PL		S	
Hoffman and O'Riain (2012b)	N	Cape Town	WC	2012	2	9	4.50				M	C			B(M)		
Hoffman and O'Riain (2012a)	N	Cape Town	WC	2012	2	8	4.00				M	C			B(M)	S	
Holmes et al. (2012)	N	Cape Town	WC	2012	2	9	4.50				M	C		PL	B (V) (M) (BI) (R) (A) (F)	S	R
Leonard (2012)	N	Durban	KZN	2012	2	4	2.00	PP (EJ) (PE)					PE (SP)				
Mather and Stretch (2012)	N	Durban	KZN	2012	2	5	2.50				M		PE (D) (CG)	PL			

Odindi and Mhangara (2012)	N	Port Elizabeth	EC	2012	2	3	1.50							PL	B(V)	S	
Odindi et al. (2012)	N	Port Elizabeth	EC	2012	2	4	2.00							PL			
O'Farrell et al. (2012)	N	Cape Town	WC	2012	2	12	6.00	PP		ES	M	C	PE (W)			S	
Olowoyo et al. (2012b)	N	Pretoria	GP	2012	2	11	5.50		HN (M)				PE (SP)		B(V)		
Olowoyo and van Heerden (2012)	N	Pretoria	GP	2012	2	0	0.00						PE (SP)				
Olowoyo et al. (2012a)	N	Pretoria	GP	2012	2	5	2.50				M		PE (WP) (WB)		B(F)		
Pauw and Louw (2012)	N	Cape Town	WC	2012	2	9	4.50	PP (CS)		ES		C			B (BI)		
Petersen et al. (2012)	Y	Cape Town	WC	2012	2	11	5.50	PP (SQI)	HN (TF) (M)			C			B (V) (FG) (I) (R) (BI) (F) (M) (A)	S	
Riemann et al. (2012)	N	Hermanus, Stanford	WC	2012	2	3	1.50				M		PE (W)	PL		S	
Roberts et al. (2012)	N	Durban	KZN	2012	2	29	14.50				M	C	PE (CG)	PL	B(V)	S	R
Roomaney et al. (2012)	N	Cape Town	WC	2012	2	2	1.00	PP (SQI)			M				B(M)		
Smit and Parnell (2012)	N	No specific		2012	2	4	2.00				M		PE (AP) (SP) (WP) (CG)			S	
Swilling et al. (2012)	N	Stellenbosch	WC	2012	2	2	1.00	PP (SQI)	HN (A)	ES	M	C	PE (W) (S) (CG) (WB)	PL	B (V) (A) (I) (R)	S	
Symes and Kruger (2012)	N	Roodepoort (Johannesburg)	GP	2012	2	2	1.00					C			B (BI)		

Taylor and Atkinson (2012)	N	Khutsong (Charletonville)	GP	2012	2	0	0.00	PP (SQI)	HN (A) (M)		M	C				S	
van Wilgen (2012)	N	Cape Town	WC	2012	2	15	7.50	PP			M	C			B(V)		
van Wilgen et al. (2012)	N	Cape Town	WC	2012	2	14	7.00				M	C			B(V)		
Wyma (2012)	N	Potchefstroom	NW	2012	2	0	0.00					C	PE (WB)		B (BI)		
Aylett (2013)	YY	Durban	KZN	2013	1	4	4.00	PP (SQI)			M		PE (CG)	PL		S	
Becker et al. (2013b)	Y	Boesmansriviermond	EC	2013	1	8	8.00						PE (WB)		B(F)		
Becker et al. (2013a)	Y	Boesmansriviermond / Kenton-on-Sea	EC	2013	1	1	1.00						PE (WB)		B(F)		
Carden and Armitage (2013)	N	Municipalities of Buffalo City, Cape Town, Ekurhuleni, eThekwini, Johannesburg, Mangaung, Msunduzi, Nelson Mandela Bay, Tshwane	WC, EC, KZN, FS, GP	2013	1	2	2.00	PP (SQI)			M		PE (W)			S	
Cartwright et al. (2013)	N	Durban	KZN	2013	1	3	3.00				M		PE (D) (CG)	PL		S	
Cilliers et al. (2013)	N	Potchefstroom, Durban, Cape Town	NW, WC, KZN	2013	1	11	11.00			ES	M	C		PL		S	
Davies et al. (2013)	Y	No specific		2013	1	2	2.00					C	PE (WB)		B(A)		
Dingaan and du Preez (2013)	N	Bloemfontein	FS	2013	1	0	0.00					C	PE (S)		B(V)		
Ernstson (2013)	Y	Cape Town	WC	2013	1	29	29.00	PP (EJ)		ES	M			PL	B		R
Ernstson and Sörlin (2013)	Y	Cape Town	WC	2013	1	16	16.00	PP (SQI)		ES	M	C				S	R
Faber et al. (2013)	N	Mariannhill area (Pinetown)	KZN	2013	1	7	7.00	PP (SQI)	HN (A)						B(V)		
Fatti and Patel (2013)	N	Atlasville (Boksburg)	GP	2013	1	9	9.00	PP (SQI)			M		PE (D) (CG)	PL			R

Fisher-Jeffes and Armitage (2013)	N	No specific		2013	1	2	2.00				M		PE (W)				
Goodness and Anderson (2013)	Y	Cape Town	WC	2013	1	0	0.00			ES	M	C		PL	B (V) (M) (BI) (R) (A) (F)	S	
Jackson et al. (2013)	N	Mbekweni (Paarl)	WC	2013	1	0	0.00						PE (WP) (WB)				
Jassat et al. (2013)	N	Johannesburg	GP	2013	1	0	0.00	PP (SQI)			M				B(M)		
Leck and Simon (2013)	YY	eThekwini (Durban) and Ugu District Municipality	KZN	2013	1	12	12.00	PP (SQI)			M		PE (CG)			S	R
Magidimisha et al. (2013)	N	Durban	KZN	2013	1	NF	N/A	PP (SQI)	HN (A)							S	
McHale et al. (2013)	Y	Kruger National Park western border	MP, L	2013	1	8	8.00		HN (TF)	ES		C				S	R
Mead et al. (2013)	N	No specific		2013	1	3	3.00				M	C	PE (WB) (CG)		B (I) (AL) (BI) (F) (V)	S	
Meek et al. (2013)	Y	Stellenbosch, Macassar	WC	2013	1	1	1.00					C	PE (S) (WB)		B(V)		
Mokotjomela et al. (2013)	N	Hout Bay, Constantia, Silvermine, Kalk Bay, Simons Town, Paarl, Franshoek, Swellendam, Hermanus	WC	2013	1	2	2.00								B (BI) (V)		
Molebatsi et al. (2013)	N	Tlhakgameng	NW	2013	1	0	0.00	PP	HN (A) (M)			C			B(V)		
Musakwa and Niekerk (2013)	N	Stellenbosch	WC	2013	1	5	5.00				M			PL		S	
Naidoo et al. (2013)	N	Durban	KZN	2013	1	1	1.00						PE (WP) (WB)		B(M)		

Ncube et al. (2013)	N	No specific		2013	1	2	2.00				M		PE (W) (CG)			S	
O'Donoghue and Shackleton (2013)	N	Port Elizabeth, East London, Fort Beaufort, Grahamstown, Port Alfred, Queenstown	EC	2013	1	2	2.00	PP (SQI)		ES					B(V)		
Ogundeji et al. (2013)	N	Soweto-on-Sea (Port Elizabeth)	EC	2013	1	0	0.00				M		PE (D) (CG)	PL			
Olowoyo et al. (2013)	N	Pretoria	GP	2013	1	NF	N/A						PE (SP)				
Pasquini et al. (2013)	N	Local Municipalities of Cape Town, Swartland, Hessequa, Mosselbay, George, Oudtshoorn, Knysna,and the Eden District Municipality	WC	2013	1	12	12.00	PP (SQI)			M		PE (CG)	PL			
Pfeffer et al. (2013)	Y	Durban	KZN	2013	1	2	2.00	PP (CS)			M		PE (AP)	PL		S	
Roberts and O'Donoghue (2013)	N	Durban	KZN	2013	1	4	4.00				M	C	PE (CG)	PL	B	S	R
Rollinson et al. (2013)	N	Pietermaritzburg	KZN	2013	1	0	0.00								B(M)		
Ruysenaar (2013)	YY	Pretoria, Germiston, Randfontein	GP	2013	1	2	2.00	PP (SQI)	HN (A)								
Schäffler and Swilling (2013)	N	Johannesburg	GP	2013	1	18	18.00	PP (SQI)		ES	M			PL	B(V)	S	R
Shackleton and Blair (2013)	N	Fort Beaufort, Port Alfred	EC	2013	1	3	3.00	PP (SQI)			M	C		PL	B		

Smith et al. (2013)	Y	Amanzimtoti, Anstey's, Durban, Little Maritzburg, Margate, Mtwalume, Port Edward, Port Shepstone, Richards Bay, Scottburg, Sezela, Sheffield, St Michael's, Submarine Bay, Umdloti, Umhlanga, Umkomaas, Uvongo, Westbrook, Willards, Zinkwazi	KZN	2013	1	0	0.00						PE (S)				
Wegelin and Jacobs (2013)	N	No specific		2013	1	2	2.00				M	C	PE (W)			S	
Wilhelm-Rechmann and Cowling (2013)	N	Municipalities of Nelson Mandela Bay, Buffalo City, Great Kei, Koukamma, Kouga, Ndlambe	EC	2013	1	1	1.00	PP (SQI)				C		PL			
Wilkinson et al. (2013)	Y	Cape Town	WC	2013	1	5	5.00	PP (EJ)		ES	M	C	PE (CG)	PL		S	R
Ahern et al. (2014)	Y	No specific		2014	0	2	N/A	PP (CS)		ES				PL		S	R
Anderson et al. (2014)	Y	Cape Town	WC	2014	0	0	N/A	PP (CE)		ES	M	C		PL	B(I) (V)		
Bulkeley et al. (2014)	YY	Cape Town	WC	2014	0	0	N/A	PP (SQI)			M		PE (CG)			S	R
Cash (2014)	YY	Jamestown (Stellenbosch)	WC	2014	0	1	N/A	PP (SQI)			M			PL		S	R
Cilliers et al. (2014)	N	No specific		2014	0	0	N/A	PP			M	C		PL	B	S	
De Lacy and Shackleton (2014)	N	Grahamstown	EC	2014	0	0	N/A	PP					PE (CG)		B(V)		
Kaoma and Shackleton (2014)	N	Tzaneen, Bela Bela, Zeerust	L, NW	2014	0	1	N/A	PP (SQI)	HN (TF)						B(V)		
Katz et al. (2014)	N	Cape Town	WC	2014	0	1	N/A					C	PE (WB)		B(R)		
Lucrezi et al. (2014)	N	Jeffreys Bay	EC	2014	0	0	N/A				M	C	PE (CG)		B(V)	S	

McQuaid and Griffiths (2014)	N	Cape Town	WC	2014	0	1	N/A						PE (WB)		B(I)		
Mosina et al. (2014)	N	Seshego, Lebowakgomo	L	2014	0	0	N/A	PP (SQI)	HN (A) (M)						B(V)		
Nzotungicimpaye et al. (2014)	Y	Cape Town	WC	2014	0	1	N/A						PE (AP)				
Pasquini et al. (2014)	N	City of Cape Town and Hessequa Local Municipalities	WC	2014	0	3	N/A	PP (SQI)			M		PE (CG)	PL		S	
Petersen et al. (2014)	Y	Cape Town	WC	2014	0	0	N/A	PP (SQI)	HN (M)			C				S	
Puttick et al. (2014)	N	Fort Beaufort	EC	2014	0	3	N/A		HN (TF) (M)		M (MC)				B(V)		
Shackleton et al. (2014)	Y	Tzaneen, Bela-Bela, Zeerust	L, NW	2014	0	2	N/A	PP (SQI)	HN (TF) (M)	ES	M			PL	B(V)	S	
van der Walt et al. (2014)	N	Potchefstroom (Tlokwe Local Municipality)	NW	2014	0	0	N/A				M	C	PE (S)		B(V)		
Wilhelm-Rechmann et al. (2014)	N	4 Eastern Cape coastal local municipalities	EC	2014	0	3	N/A	PP (SQI)				C		PL			

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Landscape history, time-lags and drivers of change: remnant natural grasslands in Potchefstroom, South Africa.

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Abstract

Context: The history of the landscape directly affects biotic assemblages, resulting in time lags in species response to disturbances. In highly fragmented environments, this phenomenon often causes extinction debts. However, few studies have been carried out on time lags in biotic response in urban settings.

Objectives: Our objective is to determine if there are time lags in the response of temperate natural grasslands to urbanization. Does it differ for indigenous species and for species indicative of disturbance and between woody grassland communities and open grasslands? Do these time lags change over time? What are the potential landscape factors driving these changes?

Methods: In 1995 and 2012 vegetation sampling was carried out in 43 sites in temperate natural grasslands in and immediately surrounding the urban area of Potchefstroom in South Africa. We calculated the density of dwellings, landscape diversity, urban age, altitude, percentage natural area, and road network density of natural areas in a 500 m buffer area surrounding each site for 1938, 1961, 1970, 1994, 1999, 2006, and 2010. We used generalized linear models to determine which time period best predicted the contemporary indigenous species richness and disturbance species richness patterns.

Results: The woody vegetation showed time lags for the indigenous and disturbance species richness patterns. Grassland indigenous species richness best corresponded to contemporary landscapes. The grassland disturbance species richness, however, showed time lags. Altitude and road network density of natural areas were the most frequent predictors of species richness. Different measures were important for different habitats, and some changed between the different sampling periods, indicating complex interactions operating in urban areas and its dynamic nature.

Conclusions: The history of urbanization affects contemporary vegetation assemblages in urban areas. This indicates potential extinction debts, which have important consequences for biodiversity conservation planning and sustainable future scenarios.

Keywords: landscape history, time lag, urban ecology, grassland, urban landscape measures, indigenous species, exotic species, disturbance indicator species.

Introduction

Researchers have long been interested in studying and explaining patterns of biodiversity in natural and anthropogenic landscapes. Many theories have been proposed on the drivers of these patterns and numerous studies compare current land-use effects with biotic assemblages (e.g. Duguay et al. 2006; Godefroid and Koedam 2003; Hansen and Clevenger 2005; Vakhlamova et al. 2014). However, an often ignored perspective is that of the impact of the history of the landscape. A study conducted in France revealed evidence of the irreversible impacts of ancient farming practices on soil nutrient availability and plant diversity of contemporary forested landscapes (Dupouey et al. 2002). Other studies also provided clear supporting evidence, indicating that many current landscape patterns are formed and directly influenced by past anthropogenic activities (e.g. Foster 1992; Gustavsson et al. 2007; Koerner et al. 1997; Rhemtulla et al. 2009) Therefore, in order to understand current observed patterns and processes of ecological systems it is critical to incorporate information on past human-mediated disturbances (Hamburg and Sanford 1986).

Not only does history affect ecosystems, but communities are often slow in reacting to disturbances and time lags occur between causes and their effects (e.g. Burel 1993; Foster et al. 2003; Gustavsson et al. 2007; Koyanagi et al. 2012; Magnuson 1990; Tilman et al. 1994). Time lags occur because processes operating in landscapes take time, relict species can remain in changed landscapes, movements across the landscape may be slow, some phenomena require certain rare concurrent conditions to take place, and time lags can be accumulated by a sequence of events (Magnuson 1990). Individual species respond in different ways to disturbances based on their life cycle characteristics and life history strategies (Chiba et al. 2009; Ewers and Didham 2006; Kuussaari et al. 2009), therefore, observed time lags vary. In vegetation, longer living trees show longer time lags than grassland and herbaceous plants (Davis 1986). Time lags of 150 – 250 years were estimated for Alaskan forests in response to climate change (Chapin and Starfield 1997; Lloyd 2005), whereas semi-natural grasslands in Sweden displayed a 50 -100 time year lag in plant species diversity changes due to changes in habitat connectivity (Lindborg and Eriksson 2004). Similarly, Helm et al. (2006) showed that in alvar grasslands of Estonia current habitat specialist species were best described by habitat configurations 70 years earlier. In Japanese semi-natural grasslands, Koyanagi et al. (2012) found that time lags differed between 30 – 50 years depending on the specific plant species functional traits.

In studying time lags, it is important to distinguish between research on exotic species and that of indigenous species. Studies of time lags in exotic species usually pertain to the time lag between introduction and eventual establishment and invasion; the focus is generally on the increase of species richness over time (Crooks 2005; Daehler 2009; Sakai et al. 2001). Studies focusing on indigenous species, however, invariably research time lags in the decrease of species richness, i.e. declines in populations or even species extinctions (Brooks et al. 1999; Hanski and Ovaskainen 2002; Kuussaari et al. 2009). Disturbances not only influence vegetation composition but severe disturbances, such as habitat destruction or fragmentation, can push species to extinction (Tilman et al. 2001). However, due to the existence of species time lags in response to these disturbances, extinction debts can occur, i.e. delayed extinctions (as per Kuussaari et al. 2009; Tilman et al. 1994). Therefore, a sobering picture is revealed of current observed extant vegetation potentially already doomed by past disturbances; a situation calling for critical reflection in fragmented contextual settings.

In urban ecological studies, there is a paucity of studies on legacy effects and time lags. The limited number of studies documenting time lags in vegetation patterns in urban areas almost exclusively pertains to the relationship between neighbourhood social characteristics and woody vegetation cover (Boone et al. 2009; Grove et al. 2014; Locke and Baine 2014; Luck et al. 2009; Pickett et al. 2008). However, these do not document responses of vegetation to a disturbance, but rather identify corresponding social contextual plant establishment periods. Nonetheless, there are a few studies on extinction debts in urban areas. Hahs et al. (2009) studied plant extinction rates in 22 cities worldwide and determined that contemporary urban areas potentially have large extinction debts. A subsequent study on European countries determined that "*irrespective of recent conservation actions, large scale risks to biodiversity lag considerably behind* *contemporary levels of socioeconomic pressures. The negative impact of human activities on current biodiversity will not become fully realized until several decades into the future*" (Dullinger et al. 2013).

This paper aims to (i) enhance research on time lags in the response of urban remnant natural vegetation to anthropogenic disturbances; (ii) address the paucity of urban re-visitation studies (Williams et al. 2005), (iii) add to long-term vegetation change studies in new locations in order to enhance global knowledge; and (iv) enhance urban research in temperate natural grasslands. Moreover, no such study has been carried out in South Africa. We answer the call in urban ecological literature to include temporal dynamics (Ramalho and Hobbs 2012) and to more fully understand mechanisms driving current vegetation patterns (McDonnell and Hahs 2013). The main objective is to determine if there are time lags in the response of temperate natural grasslands to urbanization. More specifically, we asked (i) does it differ for indigenous species and disturbance indicator species and between woody grassland communities and open grasslands? (ii) Do these time lags change over time? (iii) What are the potential landscape factors driving these changes?

We hypothesize that: (a) Indigenous species patterns will correspond to past landscape patterns. (b) Disturbance indicator species richness will correspond to periods of rapid urban growth and will have short time lags. (c) Woody grassland communities will have longer time lags than grasslands. (d) Intensification of disturbances (such as rapid urban growth) will shorten observed time lags.

Methods

Study area and history

The study was conducted in the city of Potchefstroom (26˚ 42′ 53′′ S; 27˚ 05′ 49′′ E) and its immediate natural surroundings, situated in the North-West Province of South Africa (Fig. 1a). The city covers a 55 km^2 area with a population of approximately 250 000 (Tlokwe City Council 2015). Potchefstroom was established in its current location in 1841 (van den Bergh 1992). Simultaneous to town settlement was the delineation of farms around the town boundary (van den Bergh 1990). However, along the western boundary of the town a town commonage area was demarcated for use as grazing (Fig. 1b). The commonage reached a maximum area of 25 434 ha by 1889 due to the continuous demand for more grazing (van den Bergh 1992). The rapid advance of the motorcar in the period from 1929 to 1945 signalled the end of the large-scale use of the town commonage for grazing purposes (Smit 1989). Therefore, the commonage area was continually grazed for about 100 years. Thereafter, urbanization and its associated disturbances became the major influence. In subsequent years, most of the urban development expanded into the town commonage area, as the most readily available municipal land (Fig. 1c). A crucial factor in the urban development of the town commonage area was the Group Areas Act of 1950, mandating the compulsory zoning of separate racial residential areas. Development of these residential areas of mostly poor residents started in 1956 in the town commonage area (Neser 1967). The democratic elections of 1994 and the lift of urban restriction laws resulted in an immense growth of the urban residential areas of the town commonage area (Fig. 1c).

Vegetation sampling

Potchefstroom is situated in temperate natural grasslands at the confluence of three vegetation types, namely the Rand Highveld Grassland, Carletonville Dolomite Grassland and the Andesite Mountain Bushveld (Mucina and Rutherford 2006). The latter being Savanna elements as found on the hills and ridges in the area (Supplementary Information Fig. S1), described in this study as woody grassland communities. The vegetation sampling sites are all situated in the town commonage area (Fig. 1b) with most on the urban-rural fringe and some existing as remnant fragments inside residential areas. Fortuitous extensive vegetation sampling of the Potchefstroom area in 1995-6 (Cilliers et al. 1999) allowed us to compare vegetation composition before and after the rapid urban expansion period. The original surveys were phytosociological relevés sampled using Braun-Blanquet cover abundance values (Mueller-Dombois and Ellenberg 1974). 78 sample plots were surveyed in 1995-6 of which 43 were re-surveyed in 2012 comprising of 26 woody grassland sites (hereafter woody) and 17 open grassland (hereafter grassland) sites. Many of the sites were lost to urban development and of the remaining sites we only chose those that were historically untransformed, i.e. we excluded old fields and any other direct anthropogenically-disturbed sites. Most of the sites are situated in the western part of the study area in an unbroken extensive grassland area, some of which later became fragmented. The rest of the sites are located on smaller fragmented remnant areas due to urbanization (Supplementary Information Fig. S2). Resampled site locations were as close as possible to the original sites, using datasheet site descriptions, aerial photographs on which some of the site locations were marked, and one of the author's (Cilliers) own recollections. Woody communities were sampled in 10 x 10 m sample plots and grasslands in 4 x 4 m sample plots (Bredenkamp and Theron 1978), with one plot per site. Woody communities are naturally occurring habitat 'islands' in the grassland matrix, mainly situated on hills and ridges forming part of the Andesite Mountain Bushveld vegetation type (Mucina and Rutherford 2006) with the dominant taxa represented by trees and large shrubs. However, five of the surveyed sites were initially grasslands in 1938, which by 1961, were encroached with various tree densities. Bush encroachment occurs due to higher rainfall frequencies (Ward 2005), which allows tree seedlings to survive in the grasslands or as a result of over-grazing and unnatural fire regimes that stimulate tree growth when competition with grassland species is lower (Kraaij and Ward 2006; Van Auken 2009).

The percentage cover of all species within the sample plots was recorded. The 1995 Braun-Blanquet cover abundance data were converted to mean percentage values (Eckhardt et al. 1993) to allow direct comparison between the resampled and original data. For this paper, only the perennial species data were used as per Williams et al. (2005) to reduce the potential for recording false absences of species. We calculated indigenous species richness (ISR), exotic species richness (ESR) and species richness of plants that indicate disturbance (DSR) per sample plot, as well as total species richness, percentage indigenous species and percentage indigenous species cover. However, the last three measures were excluded from our analyses because they all correlated with either ISR or ESR. For instance, ISR correlated highly and significantly with total species richness in both years and for both woody and grassland communities (Person's $r \geq 0.98$). Furthermore, ESR correlated highly with percentage indigenous species ($-0.86 < r < -0.97$) and percentage indigenous species cover ($-0.68 < r < -0.83$). To calculate DSR we identified 31 species from the recorded species occurrences that indicate grassland vegetation in poor condition, specifically overgrazing and trampling, pioneer species, weeds, invaders, and bush encroachment (e.g. Bezuidenhout et al. 1994; Bredenkamp et al. 1989; Cilliers and Bredenkamp 1999; Cilliers et al. 1999; Louw 1951). Because humans disturb natural areas in various ways, through trampling, plant removal, rubbish dumping etc., we wanted to determine whether these species that flourish in disturbed environments increase with increasing urbanization and if their richness patterns correspond to urban landscape measures. These disturbance indicator species were identified from published studies of Potchefstroom and its surrounding regional grassland setting (Supplementary Information Table 1).

Urban landscape measures

We digitized 500 m buffer areas around each site to quantify the landscape matrix. Optimal matrix scales have not been determined to study the effects of urbanization on vegetation (Dauber et al. 2003), therefore we decided on 500 m as some authors state this a suitable buffer area (e.g. Duguay et al. 2006; Kleijn et al. 2009; Tscharntke et al. 2005; Vakhlamova et al. 2014). Additionally, since we are interested in the anthropogenic effects on vegetation dynamics and the area of interest is mostly inhabited by poor residents, we analysed firewood collection distances. The field data sheets of Cilliers in 1995-6 revealed that sites, where firewood was gathered, were all situated within 200-500 m from residential areas. The limited literature on grassland species dispersal also indicate that most dispersal of grassland species, excluding long-distance dispersal by animals, occur well within the 500 m limit of our buffer zone (Morgan 1995; O'Connor 1991).

Measures were calculated for the time periods 1938, 1961, 1970, 1994, 1999, 2006, and 2010 as these were the dates for which we could readily obtain aerial or satellite imagery. For 1938-1994, we georeferenced digital aerial photographs, procured from government archives (www.ngi.gov.za), in ArcMap 10 (ESRI 2010) using digital topographical maps of periods nearest to the imagery dates as reference material. For the periods 1999-2010 we obtained orthorectified satellite imagery. The chosen measures for this study included: Age of urbanization (Age), altitude, road network density of natural areas (RNDN), percentage natural area (PN), density of dwellings (CD) and landscape diversity (H). These measures were calculated in ArcMap 10, additionally using the Hawth's Analysis Tools version 3.27 (Beyer 2006) add-in to calculate RNDN, CD and H. To determine the age of urbanization we used the aerial and satellite images to determine when any form of urban buildings first occurred in the 500 m buffer, for example if urban infrastructure occurred in 1938, the age of urbanization in the 2012 models was 74 years. Because we could not accurately state in which year urbanization occurred before 1938, all the urbanized sites in the 1938 GLM models were given the age of 1 year (in a sense presence/absence data). We included altitude as the sampling site locations varies from plains to foot slopes and small hills and ridges. Altitude varied from 1332 to 1432 m. The different altitudes were obtained by recording it with a GPS device at each site.

The effects of roads and trampling on vegetation are well documented (Cilliers and Bredenkamp 2000; Deng et al. 2011; Gelbard and Belnap 2003; Hansen and Clevenger 2005; Kissling et al. 2009). We specifically wanted to determine the effect of roads (tar and dirt) and footpaths on the vegetation dynamics of natural areas as an index of fragmentation and disturbance, i.e. habitat quality. Therefore, all the roads and footpaths inside and traversing the natural areas were digitized. We used the standard road network density measure (e.g. Hahs and McDonnell 2006), but the clipped roads inside the natural area were divided by the size of the natural area inside each 500 m buffer area only. Thus, road network density of natural areas (RNDN) was measured as the length of roads per m^2 of natural areas. The percentage natural areas were simply the proportion of natural areas inside the 500 m buffer area. We used the measure density of dwellings as a surrogate for population density for two reasons; first we could accurately digitize it for each time period as there are no reciprocal fine scale census data available for any of the time periods. Secondly, comparison in the literature showed that in PCA and FA analyses where both measures were used, it had similar loadings as the population density measure (Andersson et al. 2009; du Toit and Cilliers 2011; Hahs and McDonnell 2006). Thus, the density of dwellings (CD) was calculated as the count of all buildings per buffer area. Landscape diversity (H) was calculated using the proportion of different habitats analysed with the Shannon Index (Shannon 1948) (after Janišová et al. 2014; Purschke et al. 2012; Romme and Knight 1982). The buffer areas were classified by manually digitizing it from aerial and satellite images into the following classes: mine dumps and excavations, natural, urban, cultivated land, plantations and water. The percentage area per class was then used as input into Primer 6 (Clarke and Gorley 2006) to calculate the Shannon index.

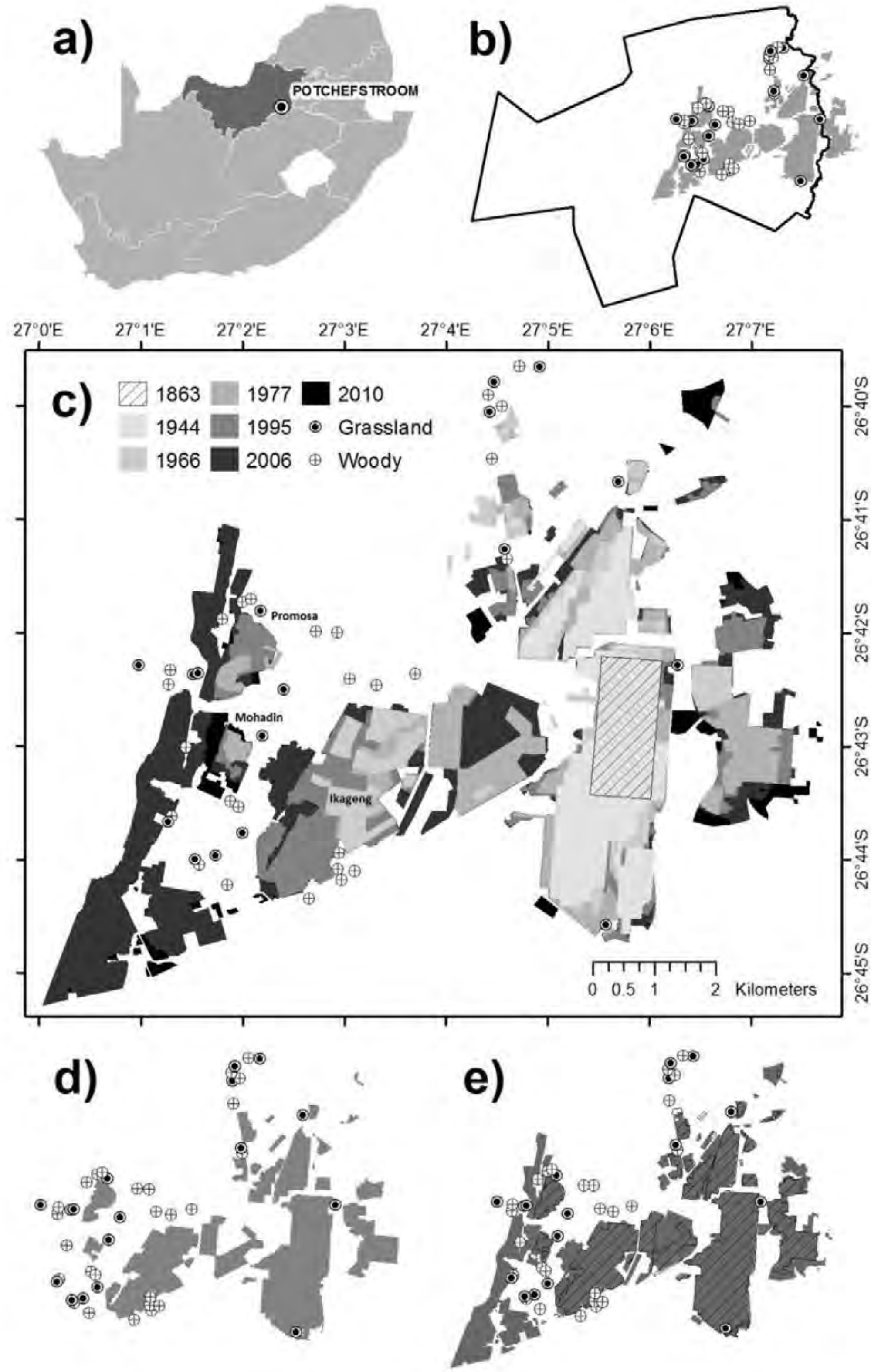


Fig. 1 The location of Potchefstroom in South Africa (a), the town commonage area (black outline) and the location of the sites (see legend of map c) (b), urban development from 1863 to 2010 (1863 obtained from an early hand drawn map, 1944-2006 were digitized from government topographical maps and 2010 from a satellite image) (c), sites and urban area in 1995 (d), sites and urban area in 2010, indicating the 1995 urban area (hatched) (e).

Data analysis

All analyses were performed with the statistical package R version 3.0.2 (R Core Team 2013). Four sets of analyses were performed per vegetation type (woody and grassland); two for the 1995 vegetation data (ISR, DSR) and two for the 2012 vegetation data (ISR, DSR). We were unable to analyse ESR due to very low numbers of exotic species in the dataset. For each analysis, the following steps were followed: In the first step, spatial autocorrelation between the sample plots were tested using Moran's I in the ape version 3.1-4 package in R. Site longitude and latitude were used to perform this test. The presence of spatial structure was further evaluated by comparing the AIC value of a null model with no covariance structure, to AIC values of models including various covariate structures (including exponential, Gaussian, spherical, linear and rational quadratics that are based on site longitude and latitude values) (the procedure is explained in full here: http://statistics.ats.ucla.edu/stat/r/faq/variogram_lme.htm). The lme command in the nlme version 3.1-111 package in R was used to perform this analysis. No indication of spatial structure was detected in any of the datasets.

In the second step, generalized linear models were performed for each of the eight vegetation parameters. The response variables were modelled following a Poisson error distribution. Predictor variables for all models included altitude, age of urbanization (Age), percentage natural area (PN), road network density of natural areas (RNDN), density of dwellings (CD) and landscape diversity (H). For the data collected in 1995, each response variable (e.g., ISR of woody vegetation in 1995) was modelled against all predictor variables for 1938, then for 1961, then 1970 and finally for 1994. Model selection was performed for each year (e.g., ISR woody for 1995 against the 1938 landscape, ISR woody for 1995 against the 1961 landscape, etc.) by removing insignificant variables one at a time until only variables of $p < 0.2$ were left in the models. AIC values of these final models for, say ISR woody vegetation for 1995, were compared between the four years (1938, 1961, 1970, 1994) and the one with the lowest AIC was selected as the optimal model for this particular vegetation parameter. For the data collected in 2012, the same procedure was followed as described above, except that the response variables here were modelled against all predictor variables for 1938, 1961, 1970, 1994, 1999, 2006, and 2010.

All variables were on a continuous scale, but a few had to be converted to categorical variables due to highly irregular values in the variable. This was particularly true for variables measured in 1938 and 1961, and a few variables in 1970.

Results

Vegetation change

Over the 17 year period between 1995 and 2012, mean ISR declined for both grassland and woody communities (Table 1). Mean ESR was very low (<2) for both grassland and woody sites in 1995 and 2012 (Table 1). Mean DSR declined in grasslands but not in the woody vegetation (Table 1). Indigenous and disturbance species richness per plot is also mapped for 1995 and 2012 in Figs 2 and 3.

Table 1 Descriptive statistics of the grassland and woody communities for the years 1995 and 2012. G = grassland, W = woody vegetation. ISR = indigenous species richness, ESR = exotic species richness, DSR = species richness of species indicating disturbance.

Variable	Mean	Min	Max	SD
Grassland				
G1995ISR	28.47	13.00	54.00	12.04
G2012ISR	20.71	7.00	32.00	7.86
G1995ESR	1.35	0.00	8.00	2.37
G2012ESR	0.76	0.00	5.00	1.30
G1995DSR	4.47	0.00	12.00	2.98
G2012DSR	2.29	0.00	8.00	2.14
Woody				
W1995ISR	27.08	10.00	42.00	9.19
W2012ISR	22.50	7.00	37.00	7.99
W1995ESR	1.12	0.00	4.00	1.28
W2012ESR	1.65	0.00	6.00	1.67
W1995DSR	4.88	0.00	12.00	3.66
W2012DSR	4.04	1	10.00	2.16

Landscape matrix change

Plots showing changes in landscape measures with time are presented (Fig. 2-5). The percentage natural area declined steadily with years; however woody sites situated on average at higher altitudes, had consistently higher average percentage natural areas left (Fig. 2). The newly adapted road network density (RNDN) of natural areas indicated that grasslands had consistently higher densities of footpaths and roads except in 2010. RNDN increased steadily with a marked increase after 1994, consistent with rapid urban development in the area (Fig. 3). From the density of dwellings, it is clear that since 1994 population density increased drastically (Fig. 4). Grassland site landscape diversity was consistently more complex than woody landscape diversity and increased from 1938 to 2010 (Fig. 5).

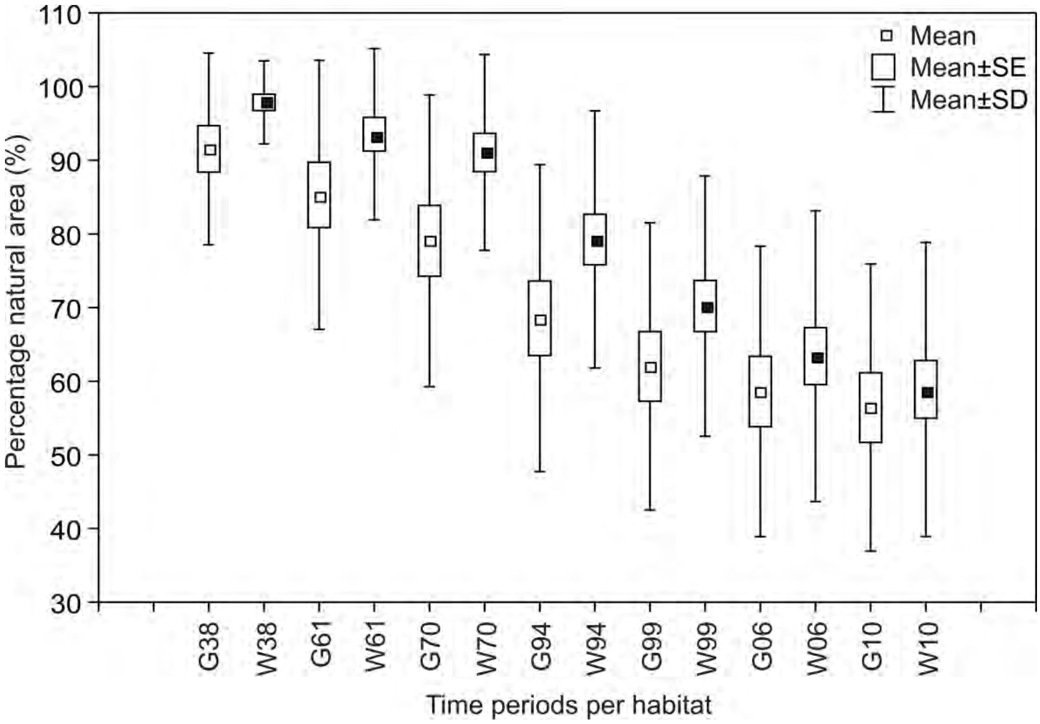


Fig. 2 Box plots indicating the change in the percentage natural (PN) area for the grassland (G) (open boxes) and woody (W) (black boxes) communities spanning the period 1938-2010.

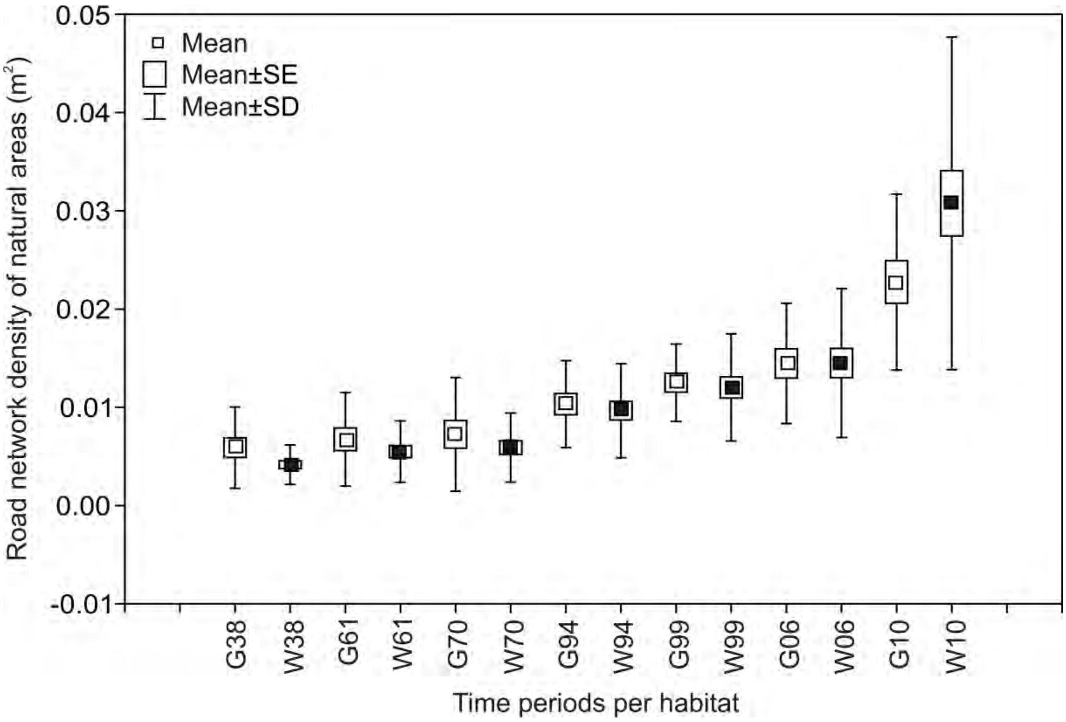


Fig. 3 Box plots indicating the change in the road network densities (RNDN) of the natural area for the grassland (G) (open boxes) and woody (W) (black boxes) communities spanning the period 1938-2010.

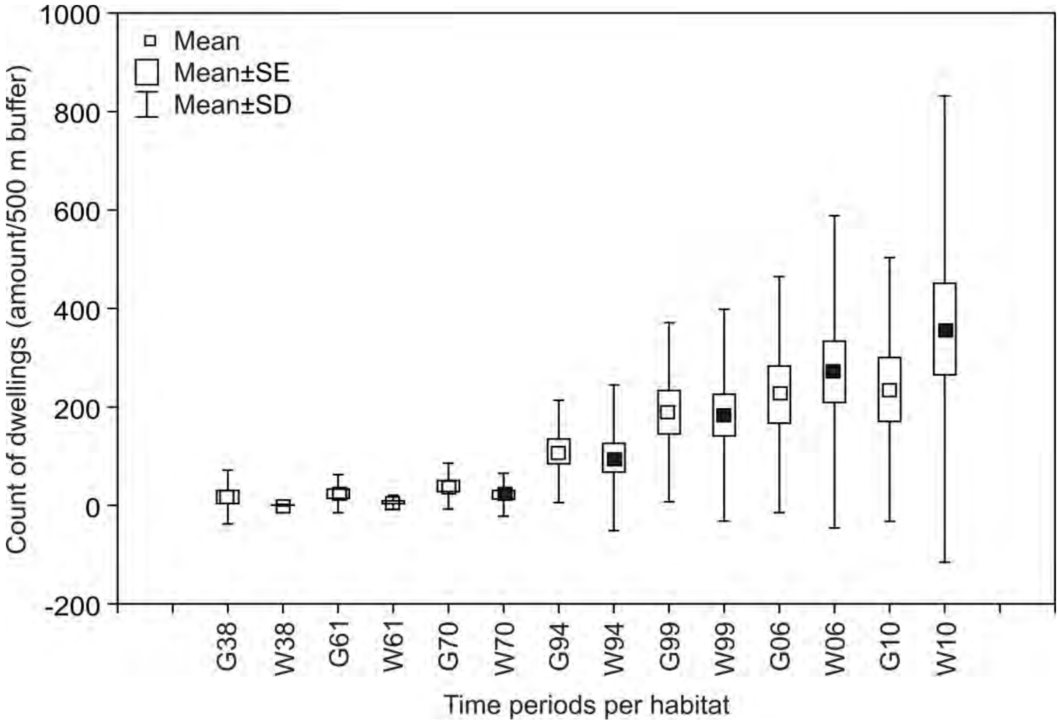


Fig. 4 Box plots indicating the change in the count of dwellings (CD) for the grassland (G) (open boxes) and woody (W) (black boxes) communities spanning the period 1938-2010.

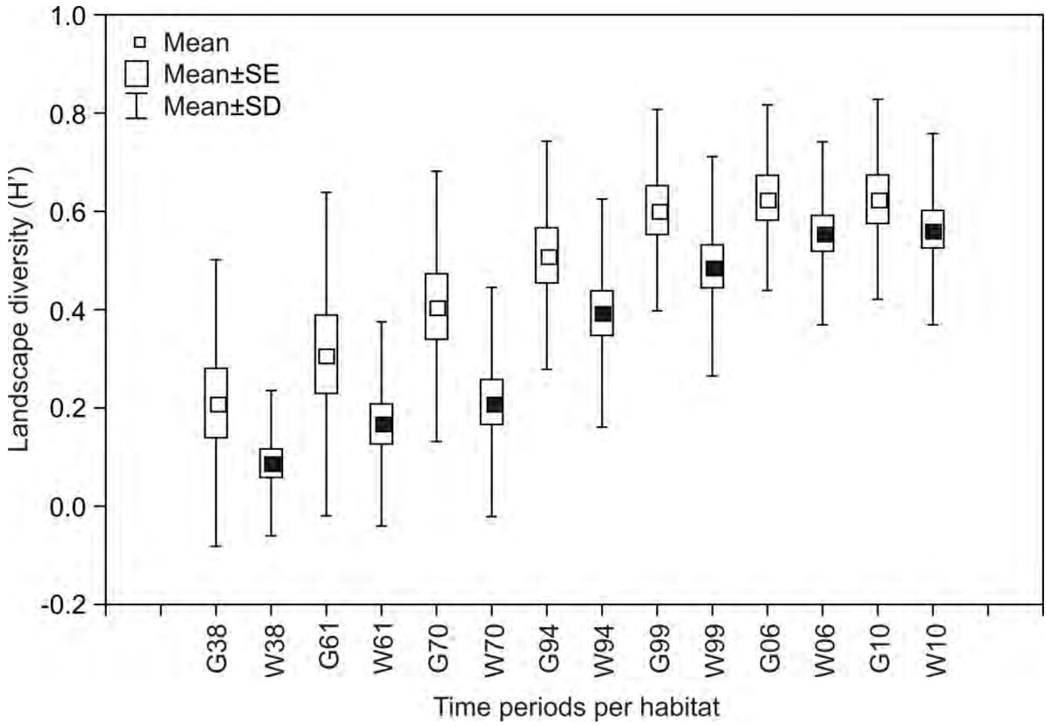


Fig. 5 Box plots indicating the change in landscape diversity (H) for the grassland (G) (open boxes) and woody (W) (black boxes) communities spanning the period 1938-2010.

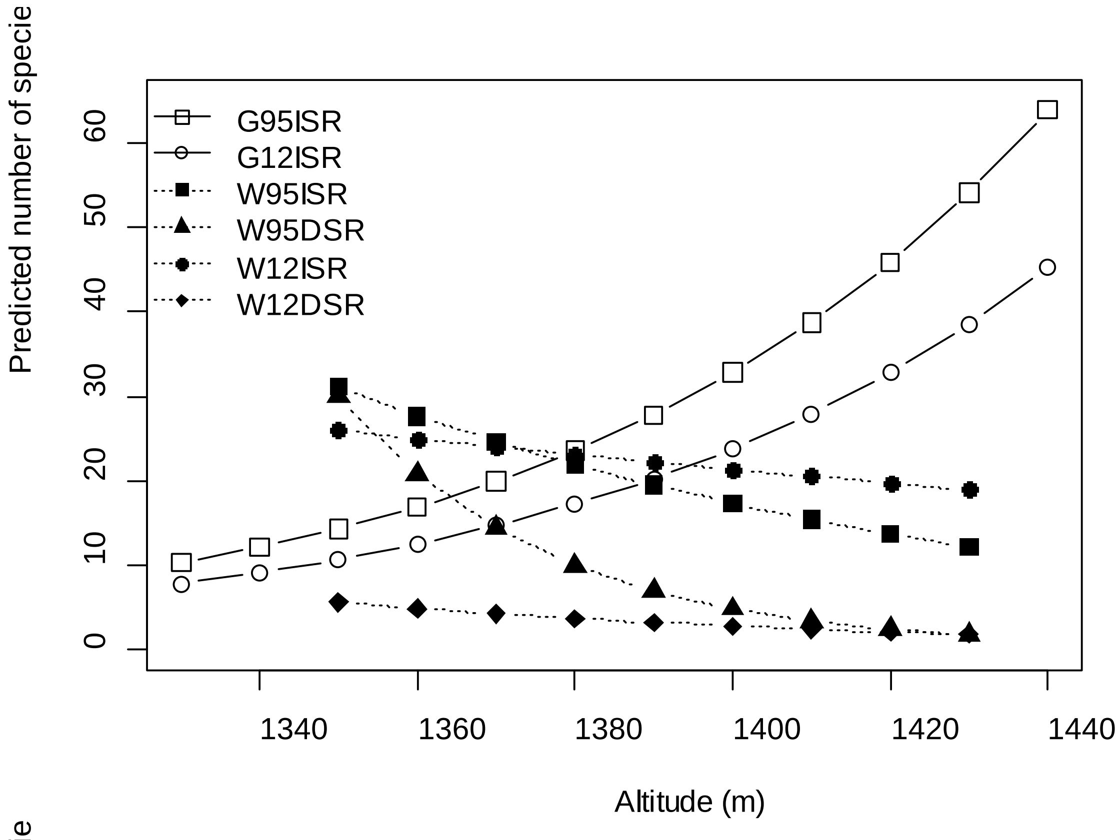
Vegetation community time lags

Results of the GLM models indicate that the woody vegetation richness patterns (ISR and DSR) showed time lags (Table 2). In 1995, ISR was best predicted by the 1970 landscape, indicating a 25 year time lag. In 2012, the best predicted model was of the 1994 landscape, indicating an 18 year time lag. The 1995 DSR was best predicted by the 1961 landscape, representing a 34 year lag. This changed to 42 years in 2012 as the 1970 landscape represented the best fit model. The grassland vegetation, however, showed no time lags for ISR (Table 2). DSR, on the other hand, was best explained by the 1970s landscape, indicating a 25 year lag. In 2012, this changed to a six year lag, best predicted by the 2006 landscape.

Altitude and road network density of natural areas (Table 2 and Fig. 6) were the most frequent predictors of species richness. Five of the eight vegetation models had a statistically significant response to both altitude and road network density of natural areas. Grassland species richness increased with altitude and RNDN, while woody species richness decreased with altitude and RNDN (Fig. 6). Percentage natural area was statistically significant in four models with grassland communities decreasing with increasing PN, while the woody disturbance species richness in 2012 increased with PN (Table 2, Fig. 7). The count of dwellings and landscape diversity were each significant in three models. The age of urbanization was the least important variable with only one statistically significant contribution in the 2012 grassland ISR model (Table 2).

Table 2 GLM results. Model coefficients (± SE) are presented, as well as p-values. Int = model intercept, Alt = altitude, Age = age of urbanisation, PN = percentage natural area, RNDN = road network density of natural areas, CD = count (the number) of natural areas, H = Shannon's diversity index of landscape diversity. AIC = Akaike's Information Criterion. AIC values represent the model with the highest AIC value (and year), and the model with the lowest AIC (and year). Coefficient values presented here are from models with the lowest AIC values. L2 and L3 represent the second and third levels of a variable classified as a factor. See Materials and Methods.

	Int	Alt	Age	PN	RNDN	CD	H	AIC (year)
Grassland								
1995								
ISR	-19.992 (5.030) <0.001	0.017 (0.004) <0.001	0.006 (0.004) 0.133	-0.007 (0.004) 0.045	39.058 (14.328) 0.006			153.40 (1938)-> 135.38 (**1994**)
DSR	3.388 (0.387) <0.001			-0.026 (0.005) <0.001				70.91 (1994)-> 67.51 (**1970**)
2012								
ISR	-20.550 (5.139) <0.001	0.016 (0.004) <0.001	0.011 (0.003) 0.002		18.750 (8.713) 0.031	0.001 (0.0003) 0.003	0.752 (0.376) 0.046	130.06 (1938)-> 116.21 (**2010**)
DSR	-0.935 (0.507) 0.065				107.187 (25.946) <0.001			69.58 (1938) -> 59.40 (**2006**)
Woodland								
1995								
ISR	20.647 (3.585) <0.001	-0.012 (0.003) <0.001		-0.285 (0.211) 0.175 (L2) -0.553 (0.228) 0.015 (L3)	-43.493 (24.447) 0.075	-0.460 (0.144) 0.001 (L2) -0.126 (0.239) 0.600 (L3)	-1.429 (0.355) <0.001	211.05 (1938)-> 178.76 (**1970**)
DSR	53.572 (9.026) <0.001	-0.037 (0.006) <0.001			-68.388 (34.550) 0.048		-0.731 (0.255) 0.004 (L2)	157.33 (1970)-> 125.66 (**1961**)
2012								
ISR	8.980 (3.196) 0.005	-0.004 (0.002) 0.080	0.005 (0.003) 0.116		-39.360 (15.070) 0.009	0.001 (0.0003) <0.001		197.46 (2006)-> 187.98 (**1994**)
DSR	21.426 (7.815) 0.006	-0.015 (0.006) 0.010		-0.036 (0.271) 0.894 (L2) 0.612 (0.294) 0.037 (L3)				113.04 (2010)-> 109.21 (**1970**)



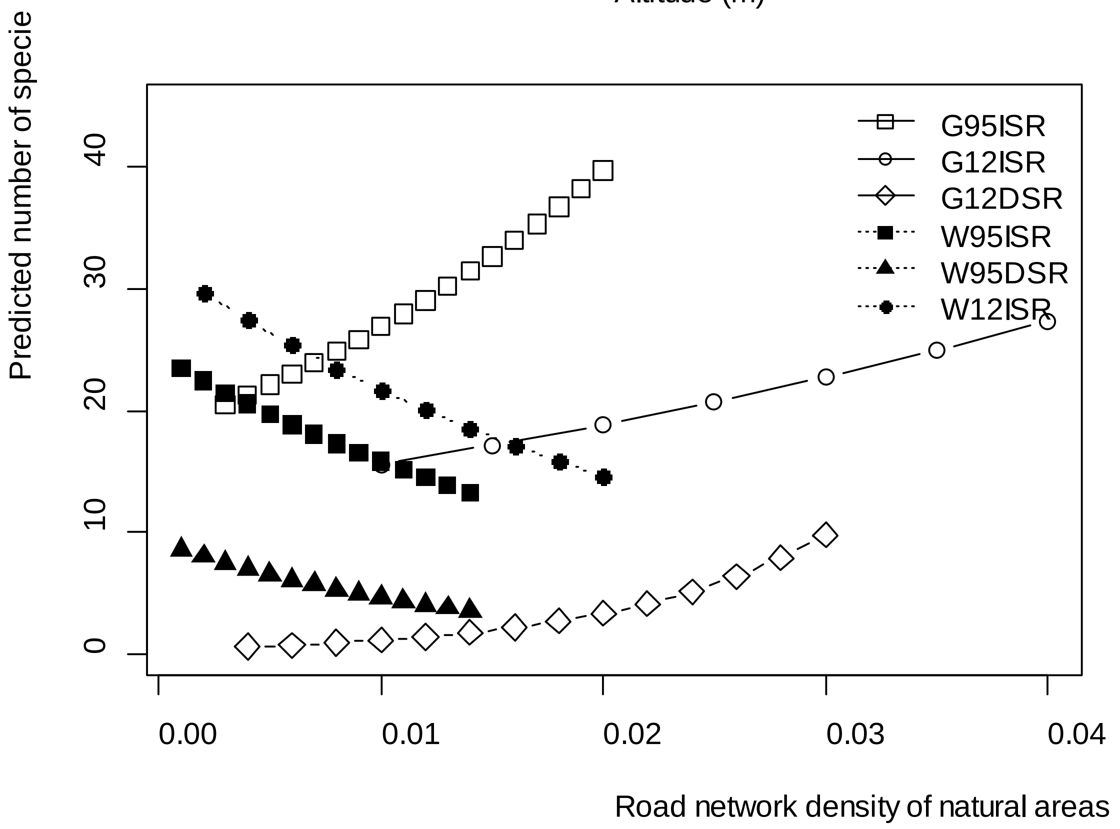


Fig. 6 The relationships between species richness and altitude (top plot) and the road network density of natural areas (bottom plot) as indicated in Table 2.

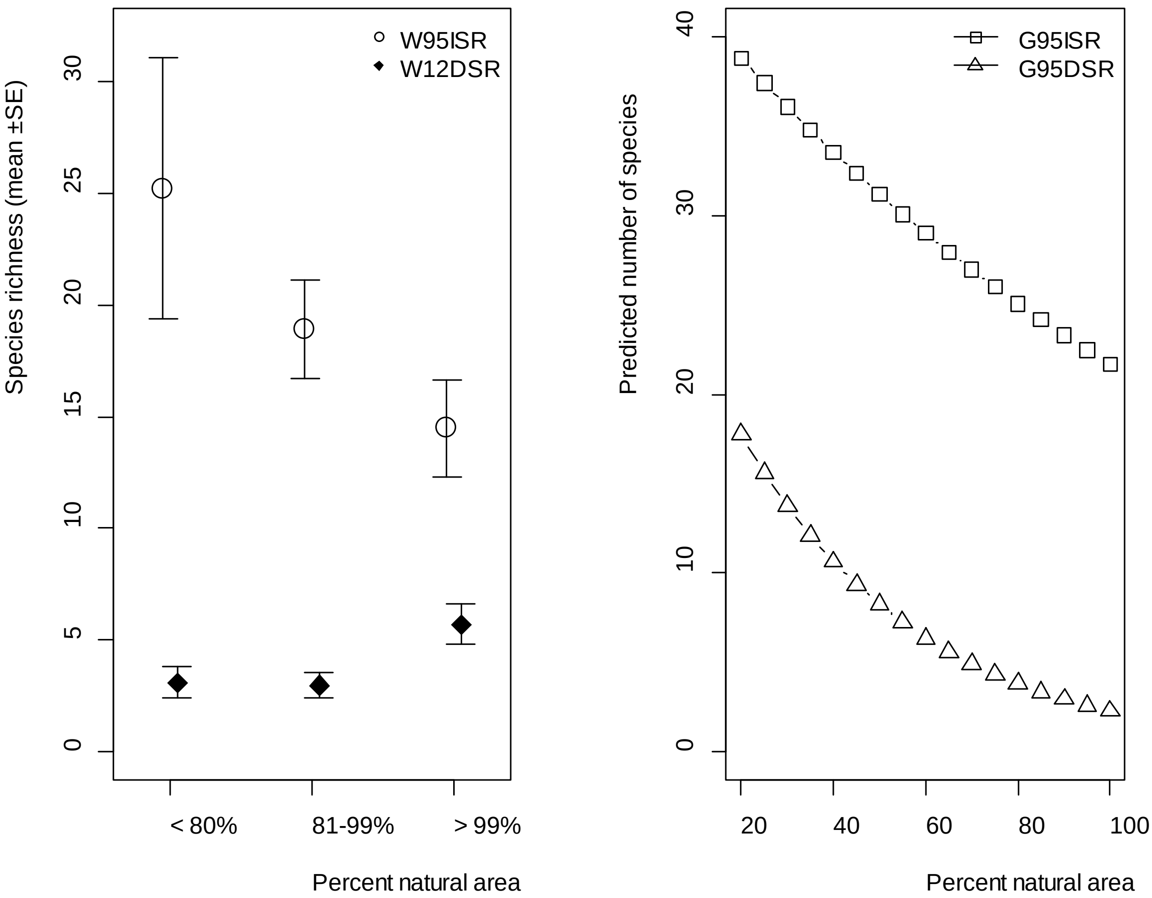


Fig. 7 The relationships between species richness and the percentage natural area as indicated in Table 2.

Discussion

The loss of indigenous species in both the woody and grassland vegetation are in line with documented loss of species in urban areas with time (Chocholoušková and Pyšek 2003; Stehlik et al. 2007; Tait et al. 2005; Williams et al. 2006). Time lags were observed for the woody vegetation and preceded major urban development in the study area. The township of Ikageng was established in 1957-1963 and in 1969 resettlement started in Promosa (Neser 1967). In the period between 1961 and 1970 the township of Mohadin was established, and 1994 preceded the start of rapid urban growth (Fig. 1). Importantly—despite the fact that the accuracy of the time lag calculation is restricted by the time periods used—the woody ISR lags remained constant at an average of 21 years, moving 'forward' with urban development. The time lags observed for woody DSR were longer than anticipated and averaged 38 years, corresponding to the first major urban development in the town commonage area. The grassland ISR patterns showed no time lags, the models were best predicted by contemporary landscapes. This confirms the results of the study of Adriaens et al. (2006) on semi-grasslands in Belgium where they found no time lags in connection with past habitat area and connectivity. However, the grassland DSR revealed time lags, corresponding to the 1970 landscape in 1995 and that of 2006 in 2012, time lags of approximately 25 and six years. There are no equivalent time lag studies carried out in temperate natural grassland with which to compare our findings. However, the observed time lags for the woody community are relatively close to the 30-50 year time lags of Japanese semi-natural grasslands (Koyanagi et al. 2012). Other studies in semi-natural grasslands document 50-100 years (Lindborg and Eriksson 2004) and 70 years for Estonian semi-natural grasslands (Helm et al. 2006).

The 1995, grassland indigenous species richness patterns were best predicted by current landscape variables where higher altitudes with smaller percentage natural areas in the buffer, higher road network densities, and more heterogeneous landscapes had the highest ISR. The 2012 richness patterns were again best predicted by current landscape variables; higher altitudes, older urbanization influence, higher road network densities, population densities and landscape diversity predicted higher ISR. The lower percentage natural areas can be explained by the fact that the higher species richness sites on the higher lying areas were situated close to urban areas and the site with the highest number of species was a linear fragment next to a main road in the urban area (GO15) (Fig. 8). These sites generally also had higher road network densities as many footpaths crisscross through them between the residential areas. In the grassland disturbance species richness models, only a single variable best predicted the patterns in 1995 and 2012. The 1995 model indicated that lower percentage natural area sites of 1970 had higher DSR. Whereas, sites with higher road network densities in 2006 predicted sites with higher DSR in 2012. Figure 8 clearly indicates that all grassland sites nearest to the urban areas of that time had higher disturbance species richness. The much shorter time lag shown in 2012 might be explained by the decline of disturbance species over the 17-year period. Another factor might be the decline in utilization of the veld by poorer residents. Therefore, despite drastic increases in population densities and urban growth, perennial grassland species indicative of poor condition declined.

For the indigenous species richness of woody vegetation, on the other hand, lower altitudes with smaller percentage natural areas in the buffer, but more homogenous and low dwelling densities in 1970 predicted sites with higher ISR in 1995. In 2012, however, lower altitudes, lower road network densities but higher dwelling densities in 1994 predicted sites with higher ISR. The lower altitude woody vegetation sites, with the higher species richness are situated closer to urban areas which accounts for the lower percentage natural areas predicting higher species richness. The subsequent positive relationship with dwelling densities in 1994 is explained by the fact that the sites with the highest species richness values in 1995 still had the highest species richness in 2012. Thus after urban growth took place these sites, situated in the densely packed township areas, now had higher dwelling densities (Fig. 9).

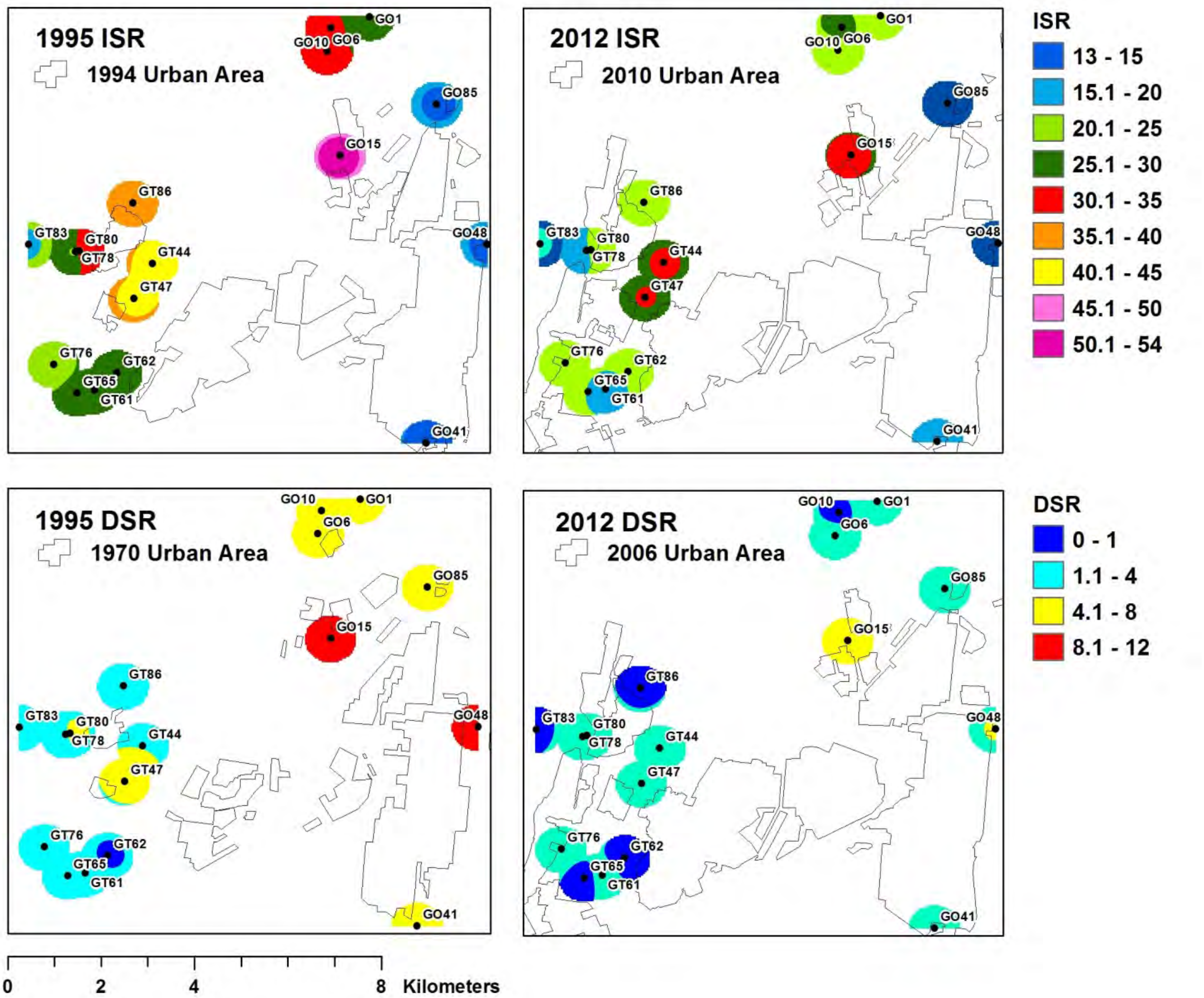


Fig. 8 Grassland indigenous and disturbance species richness per site for 1995 and 2012.

The woody disturbance species richness in 1995 was best predicted by the 1961 landscape, indicating that lower altitude, lower road network density, and more homogenous sites had higher species richness. In 2012, lower altitudes with less natural area in the buffer had higher DSR values. The sites nearest to urban areas are on average situated at lower altitudes, and the contradictory lower road work densities can be ascribed to the fact that the road network values for 1961 was highest in sites W018, WO8, and WO9. Sites WO8 and WO9 are very small isolated rocky outcrops in a grassland matrix, hence the low overall species richness and disturbance species richness (Fig. 9). However, many footpaths crossed this area then, due to the vicinity of military grounds and a water purification plant as well as the fact that it is situated on a relatively small vegetation fragment due to a large eucalyptus plantation above the site and its close proximity to a main road. In contrast, sites in the non-fragmented western part of the study area—despite the nearness of many to urban areas— still had fewer roads and footpaths in relation to the size of natural areas, therefore, the road network density measure predicted that lower densities had higher DSR values.

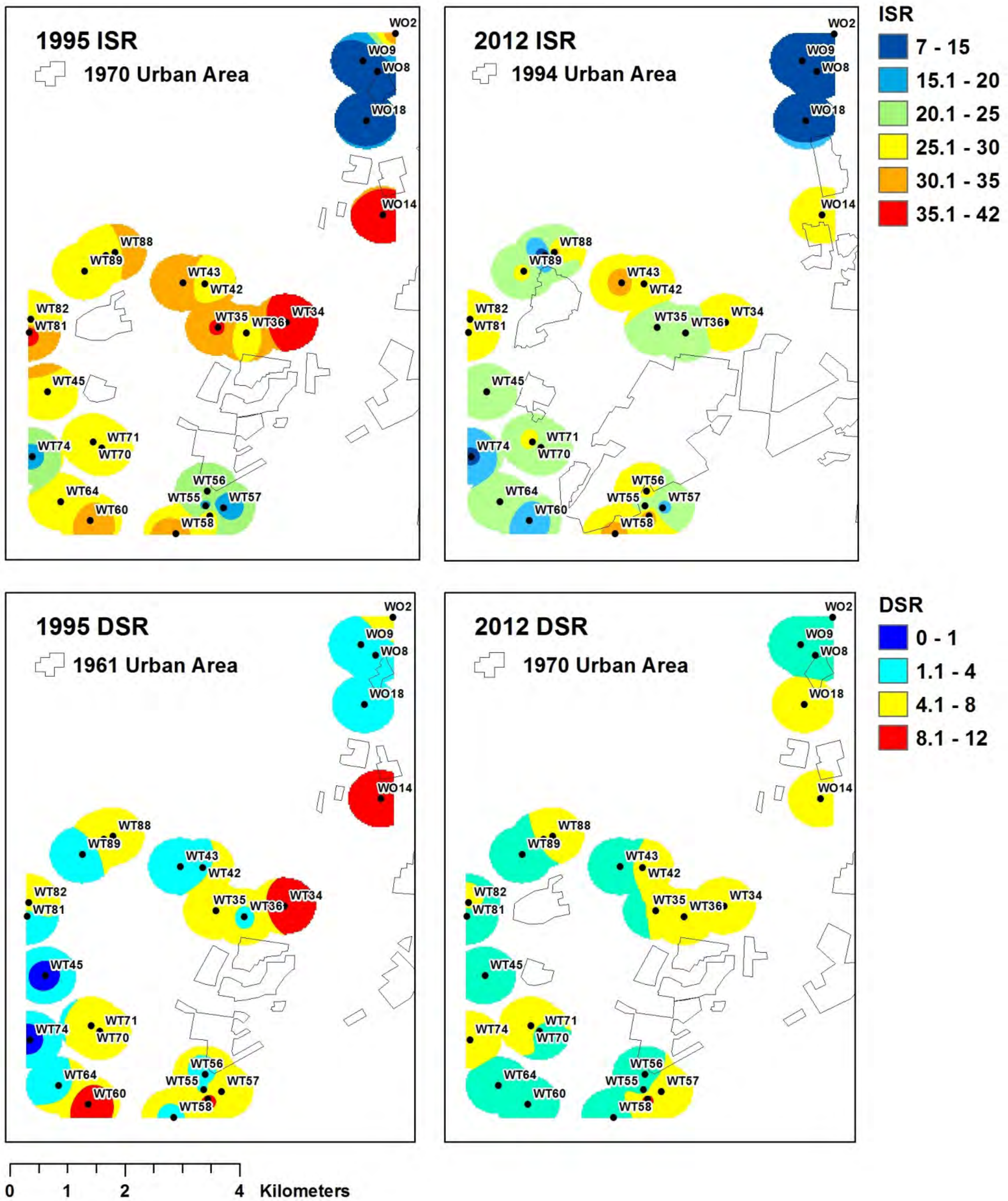


Fig. 9 Woody indigenous and disturbance species richness per site for 1995 and 2012.

Natural stressors in these grasslands are grazing, climate and fire. In our study area, fire is suppressed at sites in the city and those on the fringe experience irregular burning. Anthropogenic and naturally-caused fires together cause changed disturbance regimes, which might also impact indigenous species richness (Williams et al. 2006). Sites situated within the urban area are regularly mown, but in those situated further away, in the urban-rural fringe, grazing has largely ceased—which also affects vegetation patterns. In their study, Williams et al. (2006) found that extinction risks of grassland species were determined by habitat quality rather than the size and isolation of the patches. Similarly, in explaining the distribution of herbaceous species in woodlands, Dupré and Ehrlén (2002) found that habitat quality was more important than spatial configuration. Additionally fragmentation effects can be masked by confounding factors (Ewers and Didham 2006). In the current study, some small fragmented areas harboured higher diversity than sites situated in the extensive grassland area in the western part of the study area, emphasizing the importance of habitat quality and site specific factors on grassland diversity. However, the overall loss of species from 1995 to 2012, even in the grasslands that exhibited no time lags, indicates the importance of fragmentation and its associated effects on vegetation communities in the study area, as also indicated by (Krauss et al. 2010). Other important factors influencing vegetation patterns are precipitation and climate (Anderson and Inouye 2001), aspects not tested in this study. Results indicate that urban areas are complex and that different components of a vegetation community react differently to disturbances. Moreover, between the different years some of the measures predicting the different vegetation diversities changed as well as their relationships (e.g. from negative to positive). The absence of time lags in the open grasslands was surprising. The urban landscape measures were determined for a 500 m radius buffer and we acknowledge that the scale we used to determine the landscape measures can have an impact on the reliability of our results. The sites that were chosen and the specific landscape measures used can also influence our results; the possibility arises that grasslands might respond to other variables not measured or at different scales.

Conclusions

Our first hypothesis that indigenous species patterns correspond to past landscape patterns was partly confirmed, as woody indigenous species showed time lags. The second hypothesis that disturbance indicator species correspond to periods of rapid growth and exhibit short time lags, was confirmed for the first part as it corresponds to the start of major urban growth and its related impacts on the surrounding vegetation. However, for the woody vegetation, DSR time lags were longer than those for ISR. In the grasslands, it was initially long and then shortened drastically. The last hypothesis that the time lags will shorten as urbanization intensifies was only true for the grassland disturbance species. Both the woody ISR and DSR showed relatively constant time lags.

Our study was the first to specifically test for time lags in the response of remnant natural vegetation to urbanization. The newly adapted measure of road network density of natural areas was one of the most frequent predictors in the models. Additionally, two different vegetation sampling periods were used, which in the case of the grassland DSR yielded different time lag periods. This highlights the importance of legacy effects on patterns observed in contemporary communities (Burel 1993; Ewers and Didham 2006). No correlation of species richness to historical landscapes is seen as evidence of an absence of an extinction debt (Adriaens et al. 2006). Therefore, if clear time lags exist between contemporary vegetation patterns and historical landscapes, this is seen as evidence for the presence of an extinction debt (Krauss et al. 2010; Kuussaari et al. 2009). The indigenous species losses over the 17-year period and the presence of clear time lags in the woody vegetation indicate that this community at least has a probable extinction debt to pay in the future. This adds to the research by Hahs et al. (2009) that contemporary cities carry potential extinction debts. This evidence from a small urban area on the mostly indirect effects of urbanization on vegetation patterns in our study is sobering. Our results add to the urgent call to better investigate the drivers and mechanisms responsible for vegetation change (McDonnell and Hahs 2013; Shochat et al. 2006). Conservation of the remaining grasslands is imperative, especially in the face of climate change and our responsibility towards maintaining sustainable cities and environments in general.

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Supplementary Information, Figures S1-S2

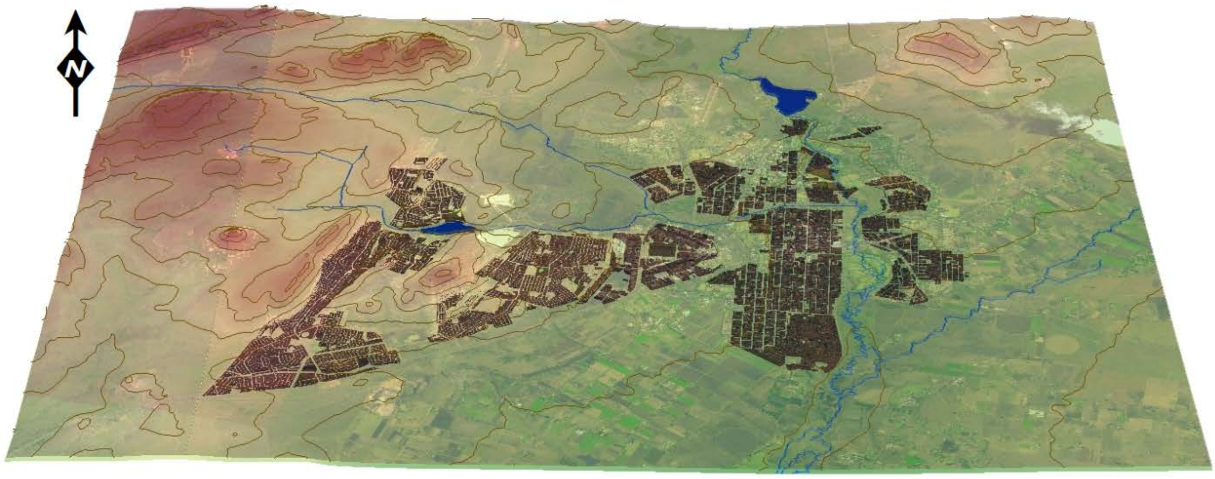

Fig. S1 Topography of the study area, indicating hills and ridges mostly in the western part of the study area.

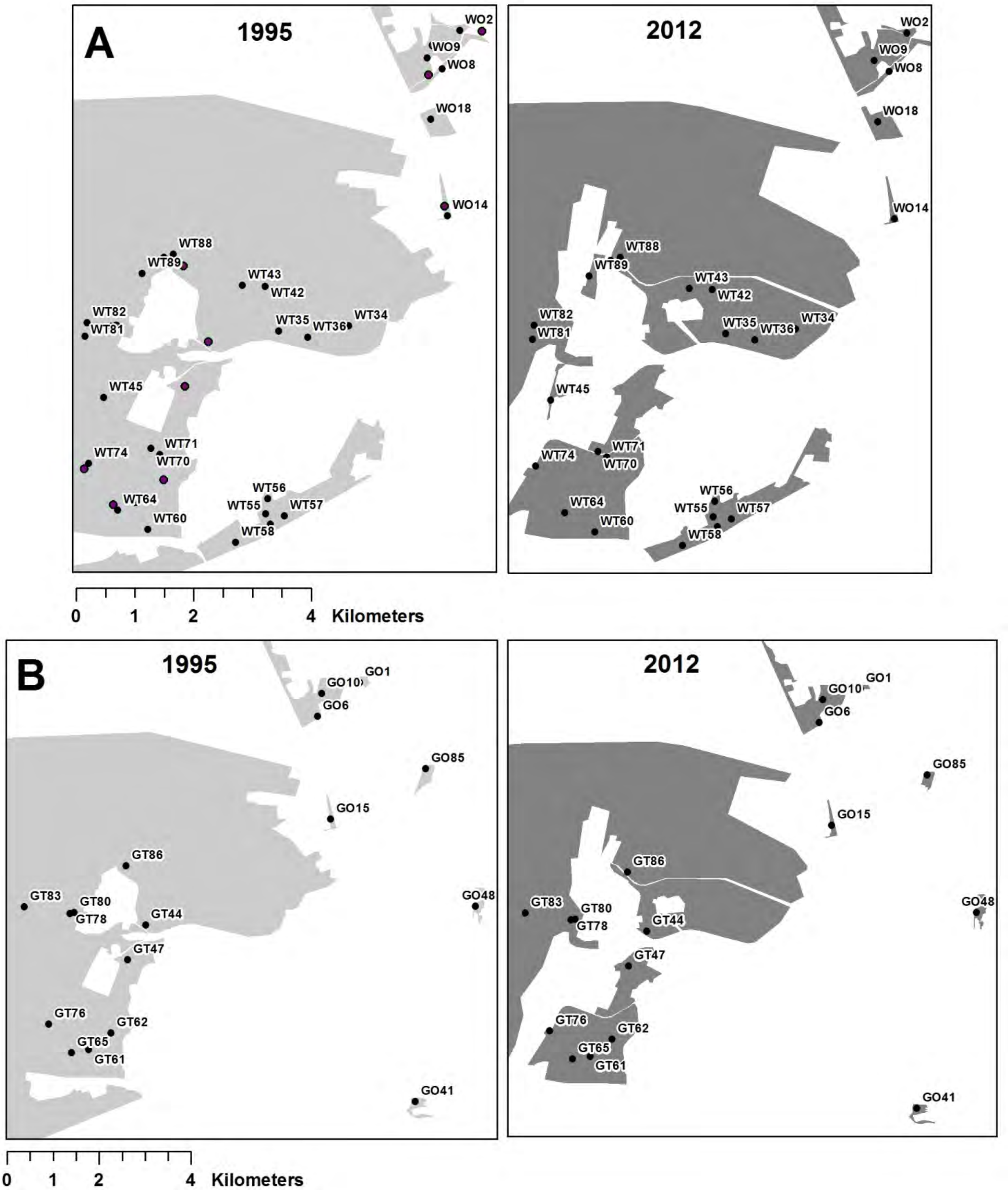

Fig. S2 Location of the woody (A) and grassland (B) vegetation sites within the natural vegetation fragments in 1995 and 2012.

Supplementary Information, Table 1 List of the 31 perennial disturbance indicator species collected during this study. Exotic species are indicated by an asterisk (*).

Species	**Reference**
*Alternanthera pungens Kunth**	(Cilliers et al. 1999; Louw 1951)
Aristida canescens Henrard subsp. *canescens*	(Bezuidenhout and Bredenkamp 1991b; Bredenkamp et al. 1994)
Asparagus laricinus Burch.	(Bezuidenhout and Bredenkamp 1990; Bredenkamp et al. 1994; Bredenkamp et al. 1989; Cilliers et al. 1999)
Asparagus suaveolens Burch.	(Bezuidenhout and Bredenkamp 1990, 1991a; Bredenkamp et al. 1994; Bredenkamp et al. 1989; Cilliers and Bredenkamp 1999; Cilliers et al. 1999; Daemane et al. 2012)
Blepharis integrifolia (L.f.) E.Mey. ex Schinz var. *integrifolia*	(Louw 1951)
Commelina africana L.	(Cilliers et al. 1999; van Wyk et al. 1997)
Conyza podocephala DC.	(Bredenkamp et al. 1994)
Corchorus asplenifolius Burch.	(Louw 1951)
Cynodon dactylon (L.) Pers.	(Bezuidenhout and Bredenkamp 1990, 1991a, b; Bezuidenhout et al. 1994a; Bredenkamp et al. 1994; Bredenkamp et al. 1989; Cilliers and Bredenkamp 1999; Cilliers et al. 1999; Louw 1951; van Wyk et al. 1997)
Eragrostis gummiflua Nees	(Bezuidenhout et al. 1994a)
Eragrostis lehmanniana Nees var. *lehmanniana*	(Cilliers and Bredenkamp 1999; Cilliers et al. 1999)
Eragrostis obtusa Munro ex Ficalho & Hiern	(Bredenkamp et al. 1989)
Eragrostis superba Peyr.	(Bezuidenhout et al. 1994a)
Eragrostis trichophora Coss. & Durieu	(Cilliers et al. 1999)
Gomphocarpus fruticosus (L.) Aiton f.	(Louw 1951)
*Gomphrena celosioides Mart.**	(Cilliers et al. 1999)
*Guilleminea densa (Willd. ex Roem. & Schult.) Moq.**	(Cilliers et al. 1999)
Ipomoea oblongata E.Mey. ex Choisy	(Louw 1951)
Ipomoea obscura (L.) Ker Gawl. var. *obscura*	(Louw 1951)
Ipomoea oenotheroides (L.f.) Raf. ex Hallier f.	(Louw 1951)
Mundulea sericea (Willd.) A.Chev.	(Daemane et al. 2010, 2012)
*Oenothera tetraptera Cav.**	(Louw 1951)
*Opuntia ficus-indica (L.) Mill.**	(Bredenkamp et al. 1994)
Pavonia burchellii (DC.) R.A.Dyer	(Bezuidenhout et al. 1994b)
*Physalis viscosa L.**	(Cilliers and Bredenkamp 1999; van Wyk et al. 1997)
Seriphium plumosum L.	(Bredenkamp et al. 1994; Daemane et al. 2012; Louw 1951)
Solanum panduriforme E.Mey.	(Cilliers and Bredenkamp 1999; Cilliers et al. 1999; Louw 1951)
*Solanum sisymbriifolium Lam.**	(Cilliers et al. 1999)
*Tragopogon dubius Scop.**	(Cilliers et al. 1999)
Urochloa mosambicensis (Hack.) Dandy	(Cilliers et al. 1999)
*Verbena aristigera S.Moore**	(Cilliers and Bredenkamp 1999)

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The impact of urbanization on temperate natural grasslands, quantifying 17 years of change in Potchefstroom, South Africa.

M. J. du Toit, S.S. Cilliers.

Abstract

Urban ecological research on the effects of urbanization processes on biodiversity is well studied. However, few researchers possess long term ecological data with which to compare contemporary biodiversity patterns. Results of such studies reveal important trends often invisible in short-term studies. In the current age of expansive urbanization and climate change realities, such information is essential to inform sustainable futures and ensure that urban areas remain as potential rich sources of biodiversity for future generations. Moreover, there is a dire need for more such studies in developing countries and especially in Africa, which is predicted to be one of the major future urban growth centres. The aim of this paper is to describe the vegetation changes in Potchefstroom over a 17-year period. Open grasslands, woody vegetation sites, and vacant lots were surveyed within the city limits. We wanted to know if the species richness and abundance of species changed within these three habitat types, whether there are differences in species composition between these habitats, and if the urbanization history influenced species composition. One -way ANOVA analyses, Wilcoxon Matched Pair tests, and Cluster Analysis were used to determine the differences within and between the different habitat types using indigenous species richness, exotic species richness, and disturbance species richness values. Results indicated that in 1995 the habitat types differed significantly from one another, however in 2012 almost half of the grassland sites resembled vacant lots, with a few others resembling woody vegetation sites. The significant decreases in indigenous species richness of woody and grassland sites have important consequences for urban grassland conservation in South Africa.

Keywords: urban ecology, temporal change, grasslands, vacant lots, remnant natural vegetation.

1. Introduction

Humans have permanently changed the earth's terrestrial environments, none more so than nature in and around cities. Urbanization processes degrade, destroy, fragment and isolate natural habitats (Alberti, 2005). Moreover, urbanization also causes biotic homogenization (McKinney, 2006; Schwartz et al., 2006). Much research has been devoted to the effects of urbanization on vegetation (e.g. Esler, 1991; McKinney, 2008; Hahs et al., 2009; Bigirimana et al., 2011; Cilliers and Siebert, 2011; Aronson et al., 2014). Urbanization generally causes the decline and extinction of native plant species (e.g. Chocholoušková and Pyšek, 2003; Tait et al., 2005; Williams et al., 2006; Hahs et al., 2009) and the increase of exotic species (e.g. Roy et al., 1999; Sukopp, 2004; McKinney, 2006; Heckmann et al., 2008). However, the focus has only lately shifted to remnant natural vegetation patches (Hahs and McDonnell, 2007). Most of this research is in forested environments (e.g. Guntenspergen and Levenson, 1997; Moffatt and McLachlan, 2004; Heckmann et al., 2008). Grasslands cover roughly 40% of the Earth’s terrestrial area (White et al., 2000) and are regarded as the most endangered ecosystem on earth (Henwood, 1998). Approximately 20% of the world's grasslands is temperate latitude grasslands (Henwood, 1998). Temperate natural grasslands include the grassland biome of South Africa, the Eurasian steppes, American prairies, Argentinean and Uruguayan pampas, the temperate grasslands of south-eastern Australia and the tussock grasslands of New Zealand

(Henwood, 1998; Mucina and Rutherford, 2006). Urban natural grassland remnants have been well studied in Australia (Williams et al., 2005; Williams et al., 2006), including a comparative study of exotic plant invasion patterns between urban grassland patches in Victoria, Australia and cities in the North-West Province in South Africa (Cilliers et al., 2008). Only a few studies have been carried out on urban remnant natural grasslands in South Africa. Research includes vegetation classification of urban open spaces in Klerksdorp (van Wyk et al., 1997), Potchefstroom (Cilliers et al., 1999), Bloemfontein (Dingaan and du Preez, 2013) and the Gauteng urban conurbation (Grobler et al., 2006). Additionally, descriptive studies on grassland vegetation composition and diversity along urbanization gradients were carried out in Klerksdorp and Orkney (du Toit, 2009) as well as Potchefstroom (van der Walt et al., 2015), the latter study is also the first to include a landscape functional analysis approach in urban environments. However, none of the studies carried out in South Africa explicitly incorporated the landscape history or were long term studies.

Historical information is most often utilized in two ways: the use of historic ecological data to quantify or determine changes in biodiversity patterns such as plant species lists (e.g. Chocholoušková and Pyšek, 2003; Van der Veken et al., 2004; Hahs et al., 2009; Gregor et al., 2012) and the use of human socio-economic history to aid in explaining current biodiversity patterns (e.g. Dupouey et al., 2002; Cousins et al., 2007; Purschke et al., 2012). Moreover, many of the temporal studies only discuss changes in species richness over time (e.g. Gregor et al., 2012), some due to the absence of abundance data or due to constraints on the accuracy of the available data (Tait et al., 2005). In this paper, we combine socio-economic history with historic ecological data of both species richness and the changes in abundance of the different species to determine the long term effects of urbanization on South African urban grasslands. Additionally, few studies have been carried out on vegetation dynamics in urban vacant lots (e.g. Garcillán et al., 2009). As part of the vegetation classification of the urban vegetation communities of Potchefstroom in 1995, Cilliers and Bredenkamp (1999) also conducted surveys on vacant lots within the urban area. Therefore, these sites could be used as comparative sites with which to determine the condition of the natural open grassland sites surrounding the city.

The aim of this paper is to describe the vegetation changes in an urban area over a 17-year period. We assessed open grasslands, woody vegetation sites, and vacant lots within the city limits. Specifically, we asked: (1) Have the species richness and abundance of species changed within these three habitat types? (2) What are the differences in species composition between these habitats?

2. Methods

2.1. Study area and history

Potchefstroom (26° 42' 53"; 27° 05' 49") is situated in the North-West Province, South Africa (inset map Fig. 1). The city covers a 55 km^2 area with a population of approximately 250 000 (Tlokwe City Council, 2015). Potchefstroom, elevation 1350m, has a mean annual rainfall of 593mm that it receives predominantly in summer months (Fig. 2). Average temperatures range between 30°C and 0°C (Fig. 2) with frequent frost in winter. Potchefstroom was established in 1838 as a settlement of Dutch farmers and settlers during the Great Trek out of the British-ruled Cape Colony (Badenhorst, 1939). A necessary addition to the town area was designated townlands for grazing; the inadequacy of its size was to become a constant complaint in the early years (van den Bergh, 1992). By 1878, the town commonage covered 25 000 ha (inset map B Fig. 1) (van den Bergh, 1992).

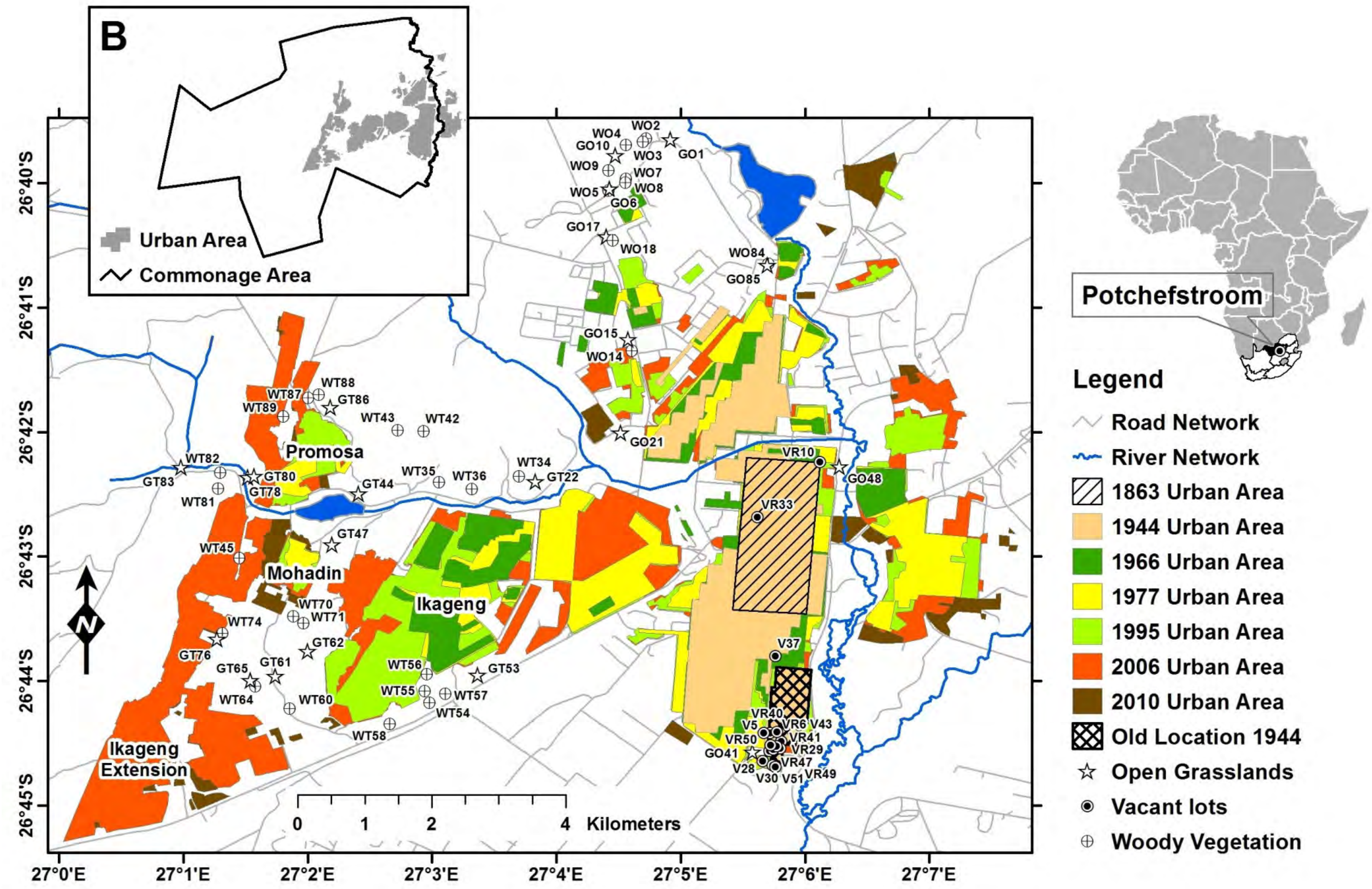

Fig. 1. Layout of the city of Potchefstroom indicating the urban development from 1863-2010. The location of the vegetation sampling sites is indicated (for labels see Table 1). The inset maps indicate the extent of the town commonage area (B) and the location of Potchefstroom in South Africa and in Africa.

The major impetuous for this was the growth of Potchefstroom as a central trading point in Transvaal, necessitating grazing for the oxen and horses used in this regard (van den Bergh, 1992). The large town commonage area inadvertently also conserved these extensive grassland areas. By the early 1900s, large scale grazing of the town commonage area ceased with the advent of trains and motorized transportation.

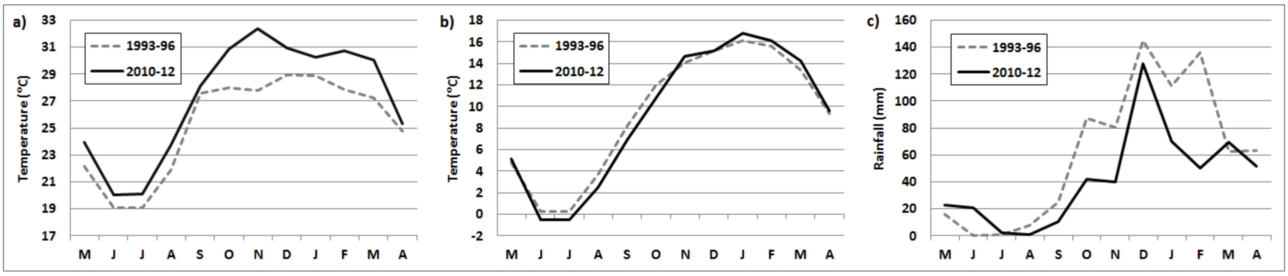

Fig. 2. The average climate of Potchefstroom for the periods 1993-96 and 2010-12 (personal communication from South African Weather Service— www.weathersa.co.za). Indicated are (a) mean daily maximum temperature per month, (b) mean daily minimum temperature per month, and (c) mean monthly rainfall. The graphs start with May to better reflect the temperature and rainfall patterns during the growing season.

The urban development history of the city is indicated in Fig. 1. The first major development period started in the 1950s. The Group Areas Act of 1950 provided for the compulsory zoning of all urban areas into exclusive group areas (Christopher, 2001). In Potchefstroom, the first segregation of residents based on their specific ethnic groups was the establishment of a separate residential area (called a "location" or township) for natives in 1888 (Neser, 1967). The location was situated at the southern end of the town (Fig. 1). The passing of the Group Areas Act resulted in the resettlement of residents into separate residential areas built in the town commonage area. The new African township called Ikageng (Fig. 1) was proclaimed in 1954, resettlement started in 1957 and was finished by 1963 (Neser, 1967). In 1956 Promosa (Fig. 1) was declared a new township for the resettlement of the Coloured population residents, with resettlement starting only in 1969 (Hellberg, 1970). Mohadin, the suburb for Indians was laid out in 1971 (Fig. 1). The site of the old location was completely cleared by the early 1970s and redeveloped in the 1980s as a white residential area. By 1995, the total Potchefstroom urban area covered approximately 2006 ha. The second major development period started after democracy in 1994. Laws governing restrictions on movement and settlement of natives in urban areas were lifted, and thousands moved to the cities. In Potchefstroom, this saw the rapid expansion of the previous township areas, and over a 15-year period the total urban area increased to approximately 3246 ha (Fig. 1).

2.2. Vegetation sampling

Potchefstroom is situated in the Grassland biome at the confluence of three vegetation types, namely the Rand Highveld Grassland, Carletonville Dolomite Grassland and the Andesite Mountain Bushveld (Mucina and Rutherford, 2006). The Andesite Mountain Bushveld is Savanna vegetation found on the hills, rocky outcrops and ridges in the study area. 30% of the Grassland Biome is considered permanently transformed with agriculture contributing 23% and urbanization 2% (Mucina and Rutherford, 2006). In 1995-6 a series of vegetation classification studies were carried out on the vegetation of the urban open spaces of Potchefstroom (Cilliers, 1998), including the natural areas (Cilliers et al., 1999) and the vacant lots (Cilliers and Bredenkamp, 1999). In 2012, after 17 years, we resampled 67 sites. Of the 78 natural sites, 52 were resampled—8 sites were developed, 15 precise location unknown, and three were unsuitable (roadside, clayey wetland grassland). Of 50 vacant lots, 15 were resampled—30 were developed, and five were unsuitable (inaccessible, more than one site on a vacant lot). The natural areas were divided into open grassland (hereafter grasslands) areas and woody grassland (hereafter woody) sites. Woody communities are naturally occurring habitat 'islands' in the grassland matrix, mainly situated on hills and ridges forming part of the Andesite Mountain Bushveld vegetation type (Mucina and Rutherford, 2006) with the dominant taxa represented by trees and large shrubs. Most of the natural sites were located around the previous township areas, the other sites are inside the town area, along the roads or near the Potchefstroom dam (Fig. 1). Due to the rapid urban expansion and the specific impacts on the vegetation in the township areas (firewood collection, removal of medicinal plants, trampling, etc), we differentiated between the sites occurring there and all the others by labelling them accordingly (Table 1). In the case of the vacant lots, we distinguished between sites that were open grasslands and became vacant lots due to normal urban expansion and those that were initially developed and later cleared to become vacant lots (Table 1). The vacant lot sites were included in this paper to determine their vegetation dynamics but also to serve as references to the change in the grassland sites. Thus, we wanted to determine if the vacant lots improved or if grassland sites degraded to resemble vacant lots.

Table 1 Description of different sites where the surveys were carried out. The date of the first urbanization influence (date of 1st Urb. Infl.) is the date on which buildings were first observed in the 500 m buffer zone. The date when the sites became vacant lots (date when 1st vacant lot) is when the site became surrounded with buildings, in the case of the VR sites, it is when the buildings were demolished, and the site was cleared.

Symbol	**Description**	**NR of sites**	**Date of 1st Urb. Infl.**
GO	Open grassland sites all other areas	9	1938-1973
GT	Open grassland sites in township areas	12	none, 1961-1999
WO	Woody vegetation sites in all other areas	10	1938-1961
WT	Woody vegetation sites in township areas	21	none, 1961-1999
			Date when 1st vacant lot
V	Vacant lot	6	1938-1973
VR	Vacant lot, previously housing	9	1961-1973

The 1995 surveys were carried out using relevés of 16m^2 for grasslands and 100m^2 for woody vegetation determined from Bredenkamp and Theron (1978). In each relevé, the cover abundance values for each species present was recorded using the Braun-Blanquet scale (Mueller-Dombois and Ellenberg, 1974; Kent, 2012). To allow comparison of the different survey periods and to ensure that the data format is correct for data analysis programs, we recorded the percentage crown cover per species for each sample plot in 2012 and converted the 1995 Braun-Blanquet cover abundance values to mean percentage values (Eckhardt et al., 1993). Additionally, we calculated the indigenous species richness (ISR), exotic species richness (ESR), and the disturbance species richness (DSR) per site. Other species richness values were also calculated (total species richness, percentage indigenous species and percentage indigenous species cover) but they all correlated with either ISR or ESR, so they were excluded (see paper 2 of this thesis). In grasslands, certain species flourish in disturbed environments indicating poor vegetation condition. We measured the DSR to determine the influence of anthropogenic impacts typical of urban areas such as roads, refuse dumping and trampling on the remnant vegetation. The chosen 49 species are species documented in the literature of the Potchefstroom region as pioneer species, weeds and invaders that establish as a result of overgrazing, trampling and bush encroachment (Supplementary Table S1). Additionally, temporal changes were further evaluated by determining the turnover of rare and dominant species in each habitat. Woody communities are harvested for firewood in the study area; to test the effect of this impact on the communities we recorded changes in life form abundance from trees to shrubs in the affected species over the 17-year period.

To determine the effect of urbanization on the observed vegetation composition the perennial species richness values (ISR, DSR) of 43 woody and grassland sites for 1995 and 2012 were correlated to six landscape measures, namely: age of urbanization (Age), altitude, road network density of natural areas (RNDN), percentage natural area (PN), density of dwellings (CD) and landscape diversity (H) (paper 2 of this thesis). The measures were calculated for the time periods 1938, 1961, 1970, 1994, 1999, 2006, and 2010 in a 500 m buffer area around each site. The results indicated that woody grassland sites and grassland DSR revealed time lags in their response urbanization; all time lags followed major urbanization events. The woody ISR had consistent time lags of about 20 years and the woody DSR showed an average time lag of 38 years. The grassland ISR showed no time lags, the grassland DSR indicating an average of 15 years. The presence of time lags in the woody species response indicates potential extinction debts. Of the measures used the altitude and RNDN were the most frequent predictors of species richness (See paper 2 of this thesis).

2.3. Data analysis

All the statistical analyses were performed with the STATISTICA 12 (StatSoft, 2002) software package. All the species indicator values (ISR, ESR, and DSR) for both years and all habitat types were tested for normality using the Shapiro-Wilk test for normality. The results of the test indicated that six of the 18 indicator values had non-normal distributions. We, therefore, evaluated parametric and non-parametric statistical analysis. To determine if there are significant differences between the mean values of ISR, ESR and DSR between the different habitat types for each year we did One-way ANOVA. Additionally, a Post Hoc Tukey Unequal N HSD test was carried out to determine which groups differed significantly from one another. Because, ANOVA analysis assumes that the data has normal distributions we also performed non-parametric Kruskal-Wallis tests. The results were the same as those of the ANOVA, so we did not include it in the paper. Non-parametric Wilcoxon matched pairs tests in STATISTICA 12 (StatSoft, 2002) were used to test for significant differences between the vegetation indices of 1995 and 2012 within each site for the vacant lot, grassland, and woody vegetation sites.

To determine the differences in species composition between the different habitat sites we did a hierarchical cluster analysis using group average linking (Clarke, 1993) in Primer 6 (Clarke and Gorley, 2006). This was based on a similarity matrix compiled in Primer 6 (Clarke and Gorley, 2006) using the Bray-Curtis similarity index with a pre-treatment square root transformation to add more weight to rare species. In addition to the cluster analysis, we calculated the average Bray-Curtis similarity values per habitat type to determine how much the average site species composition changed from 1995 to 2012 for each habitat type.

A further in-depth analysis of the woody site species composition was carried out based on the life form change of the species occurring as shrubs and trees in the sites over time. Within the study area, many woody species are harvested for firewood due to lack of electricity availability and its use for household cooking and heating where many only use electricity for lighting to save money. Cilliers et al. (1999) documented many signs of firewood collecting in the sampling sites in 1995.

3. Results

In 1995 the total species recorded for the 67 sites (those resampled in 2012) was 309 (83% indigenous) species. The 2012 sites contained a total of 298 (74% indigenous) species (see Supplementary Table S2 for a combined species list of all recorded species in 1995 and 2012). Two hundred and thirty-five of the species recorded occurred in both 1995 and 2012. Twenty-four of the species recorded in 2012 are listed as declared invasive plants according to the Conservation of Agricultural Resources Act, 1983 (Act No 43 of 1983) (CARA) amended in 2001 (Supplementary Table S3). Thirteen of these were also recorded in the 1995 sites. Of the 309 species recorded in 1995, 74 were not recorded again (8 indigenous grass species, 47 (five exotic) herbs, 17 (two exotic) shrubs and two trees) (Supplementary Table S4). However, 35 of these species were recorded as still present in the Potchefstroom area by other studies (du Toit, 2009; Jansen van Rensburg, 2010; van der Walt, 2013). Of the 39 species not subsequently recorded again 28 occurred in only one plot. In 2012, 61 species were recorded which were not present in the plots 17 years earlier. However, only nine of the species are ‘new’ in the area, of which seven are exotic garden escapes, and two are indigenous species from elsewhere in South Africa (Supplementary Table S5). Thirty-four were recorded in other communities in Potchefstroom, nine are listed in other literature on the Potchefstroom area around that time and ten are listed as occurring in the region in a plant distribution book of the northern provinces of South Africa.

The total species richness of the vacant lots increased from 87 in 1995 to 139 in 2012. Both indigenous and exotic species increased, as well as annual and perennial plants and all life forms (Table 2). However, proportionally, the exotics increased and there is also a slight increase in trees and shrubs, with a subsequent decline in the percentage contribution of the herbaceous species (Table 2). The total species richness of the grasslands declined from 209 in 1995 to 156 in 2012. All species composition values decreased in all the categories, except for the single tree species. However, the proportional representation of all the categories remained virtually the same (Table 2). There was a slight increase in the percentage perennials. The total species richness of the woody sites declines from 207 in 1995 to 178 in 2012. All species composition values decreased in all the categories, except for an increase in exotic species and the number of annuals remained the same. Again the proportional representation of the categories remained unchanged, except for the proportion indigenous species that declined by five percent (Table 2).

The comparison of the ISR, ESR and DSR differences between the different habitats for the different years indicated that the vacant lot ISR and ESR differed significantly from the grasslands and the woody sites in 1995 (Table 3). The 1995 DSR showed no significant differences between the habitats (Table 3). In 2012, the ISR means were only significantly different between the vacant lots and the woody sites (Table 3). ESR differed significantly for all habitat combinations, with significant differences between the vacant lot DSR and the grasslands and the woody sites in 2012 (Table 3). Comparison of the values of the different habitat types over the 17-year period indicated that in the vacant lots ISR and ESR increased significantly (Table 4 and 5). In the grasslands, all variables (ISR, ESR, DSR) decreased significantly (Table 4 and 5). For the woody sites, only the ISR and DSR showed significant decreases (Table 4 and 5).

Table 2 Species compositional information for each habitat type in 1995/6 and 2012. Percentage values are given in brackets and in 2012 changes are indicated by - (less), + (more), and = (similar) signs.

	Origin		**Lifespan**		**Life form**				
	Indigenous	**Exotic**	**Annual**	**Perennial**	**Tree**	**Shrub**	**Grass**	**Herb**	**Total SR**
1995									
Vacant lots	51 (58.6)	36 (41.4)	30 (34.5)	57 (65.5)	2 (2.3)	6 (6.9)	22 (25.3)	57 (65.5)	87
Grasslands	186 (89)	23 (11)	41 (19.6)	168 (80.4)	1 (0.4)	27 (13)	46 (22)	135 (64.6)	209
Woody communities	176 (85)	31 (15)	34 (16.4)	173 (83.6)	18 (8.7)	44 (21.2)	37 (17.9)	108 (52.2)	207
2012									
Vacant lots	75 + (54)	64 + (46)	45 + (32.4)	94 + (67.6)	7 + (5)	13 + (9.4)	34 + (24.5)	85 + (61.1)	139 +
Grasslands	138 - (88.5)	18 - (11.5)	26 - (16.7)	130 - (83.3)	1 = (0.6)	18 - (11.5)	39 - (25)	98 - (62.8)	156 -
Woody communities	142 - (79.8)	36 + (20.2)	34 = (19.1)	144 - (80.9)	17 - (9.5)	34 - (19.1)	35 - (19.7)	92 - (51.7)	178 -

Table 3 One-way ANOVA results between habitats for 1995 and 2012 for the indigenous species richness (ISR), exotic species richness (ESR), and disturbance species richness (DSR) (V = vacant lot, G = grassland, W = woody).

	One way ANOVA	**Post hoc Tukey Unequal N HSD**
1995 ISR	$F_{(2,64)} = 21.8657$, p = **0.00000**	VW and VG
1995 ESR	$F_{(2,64)} = 17.1351$, p = **0.000001**	VW and VG
1995 DSR	$F_{(2,64)} = 0.0621$, $p = 0.939882$	—
2012 ISR	$F_{(2,64)} = 4.7409$, p = **0.012023**	VW
2012 ESR	$F_{(2,64)} = 98.7955$, p = **0.00**	VW, VG and GW
2012 DSR	$F_{(2,64)} = 22.127$, p = **0.00000**	VW and VG

Table 4 Results of the Wilcoxon Matched Pairs Test within the different habitats (V = vacant lot, G = grassland, W = woody) between the different years for the indigenous species richness (ISR), exotic species richness (ESR), and disturbance species richness (DSR). Bold p-values are significant at p <.05000.

	Valid N	**T**	**Z**	**p-value**
V95 ISR & V2012 ISR	15	8.5	2.925003	**0.003445**
V95 ESR & V2012 ESR	14	0	3.295765	**0.000982**
V95 DSR & V2012 DSR	13	17.5	1.956798	0.050372
G95 ISR & G2012 ISR	21	1.5	3.962372	**0.000074**
G95 ESR & G2012 ESR	13	13.5	2.236341	**0.02533**
G95 DSR & G12 DSR	18	2.0	3.636455	**0.000276**
W95 ISR & W2012 ISR	31	114.5	2.616139	**0.008893**
W95 ESR & W2012 ESR	25	121	1.116637	0.26415
W95 DSR & W12 DSR	27	78.0	2.666775	**0.007659**

Table 5 Descriptive statistics of the various vegetation diversity indices (ISR = indigenous species richness, ESR = exotic species richness, DSR = disturbance species richness) for each year and habitat (V = vacant lot, G = grassland, W = woody).

Variable	**Valid N**	**Mean**	**SD**	**Min**	**Max**
V1995 ISR	15	9.60	7.18	3	25
V1995 ESR	15	8.20	2.73	3	12
V1995 DSR	15	8.53	3.31	3	14
V2012 ISR	*15*	*15.20*	*8.96*	*3*	*37*
V2012 ESR	*15*	*16.53*	*4.36*	*8*	*24*
V2012 DSR	*15*	*10.67*	*3.15*	*5*	*17*
G1995 ISR	21	32.71	12.90	14	62
G1995 ESR	21	2.86	3.54	0	12
G1995 DSR	21	8.29	5.64	0	18
G2012 ISR	*21*	*22.81*	*8.61*	*7*	*36*
G2012 ESR	*21*	*1.71*	*2.26*	*0*	*7*
G2012 DSR	*21*	*3.90*	*3.032*	*0*	*11*
W1995 ISR	32	27.66	10.31	11	49
W1995 ESR	32	3.88	2.30	0	10
W1995 DSR	31	8.03	4.39	1	18
W2012 ISR	*32*	*23.03*	*8.54*	*8*	*42*
W2012 ESR	*32*	*4.44*	*3.22*	*0*	*12*
W2012 DSR	*31*	*6.06*	*2.98*	*2*	*16*

The cluster analysis clearly indicates that the species composition differs between the habitat types and they sort into three distinct groups (Fig. 3 and Fig. 4). In the 1995 analysis (Fig. 3), in the vacant lot group no evident differentiation was found between the natural vacant lots and the cleared building sites vacant lots. Two grassland sites (GO85 and GO48) grouped with the vacant lots, however both of these are within the city limits experiencing fragmentation and disturbance effects since 1938, as they were situated next to canals or water furrows disused later on. The woody site (WT57) was highly disturbed in 1938 and fragmented through the years with urban influences since 1966. Inside the grassland group, there was no specific differentiation between grasslands located in the township areas and the others. The woody site (WT81) is situated on a lower foothill near a road that might be the reason for its grouping with the grassland sites. The two vacant lots (V5 and V28) that group with the grassland sites are both sites that were previously open grasslands at the urban periphery that were enclosed within residential areas due to urban development in 1984. Subsequently, they harboured higher species richness and more indigenous species than the other vacant lots. Inside the woody group, a clear distinction could be made between the sites in the township areas and those situated in other locations.

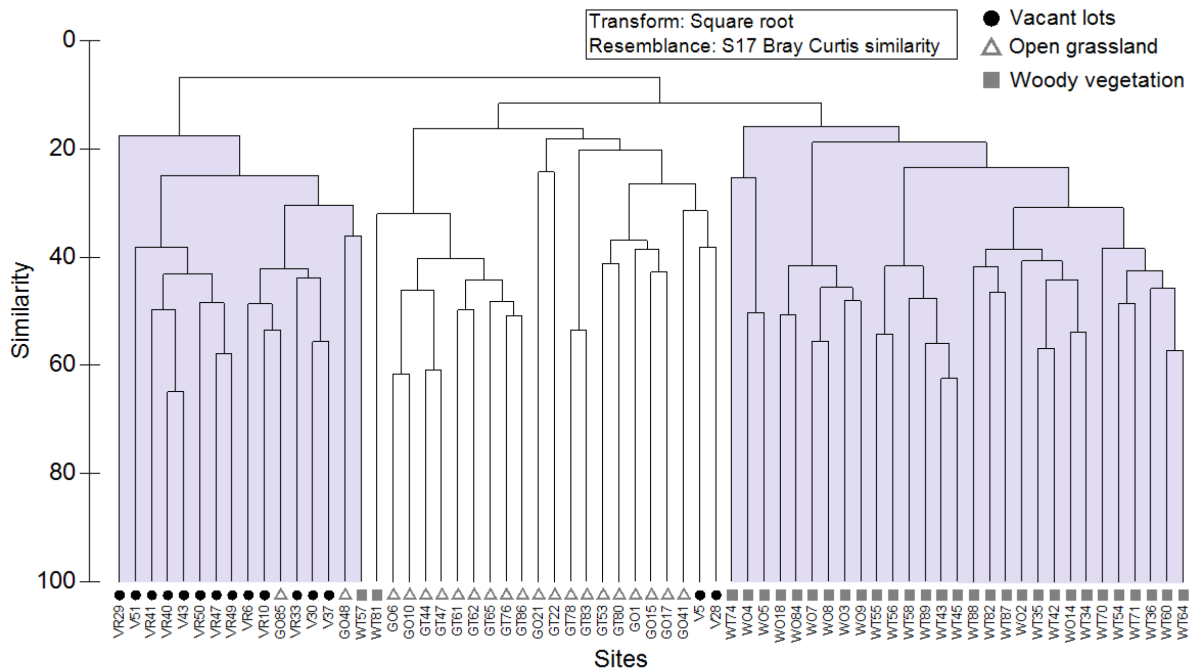

Fig. 3. Hierarchical cluster analysis of all habitat plots for 1995, based on all species similarity. Labels as described in Table 1.

In the 2012 cluster analysis (Fig. 4) the grassland group shrank, with six additional sites grouping with the vacant lots and three sites now included within the woodland group. The two vacant lot sites that grouped with the grasslands in 1995, now group with the other vacant lots. The woody site included with the grasslands in 1995 now groups with the other woody sites, as with the site that grouped with the vacant lots. A new woody site (WT74) now groups with the vacant lots. This site had no urbanization influences in 1994, but by 1999 had 30% urbanization cover in the 500 m buffer area, with buildings starting adjacent to the site. In the woody group, three grassland sites are now included (GO15, GO17, and GT80). In GO15 and GO17, the tree *Vachellia karroo* was present, and both had woody cover at some stage before 1994.

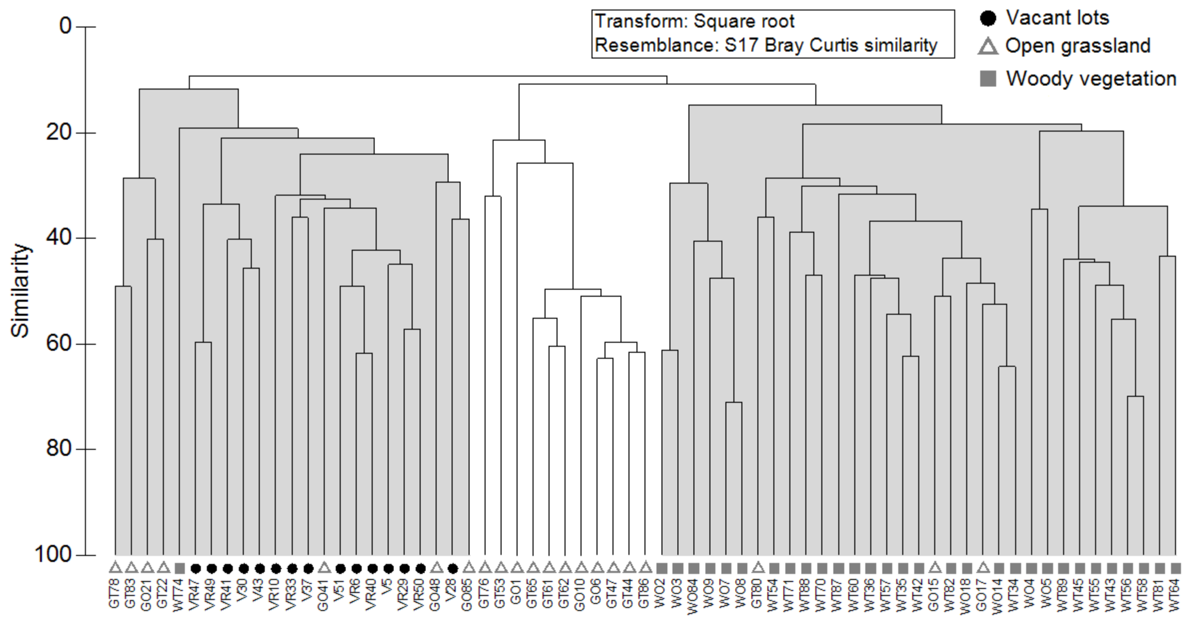

Fig. 4. Hierarchical cluster analysis of all habitat plots for 2012, based on all species similarity. Labels as described in Table 1.

The distribution of the rare species indicate that for the vacant lots the number of rare species increased from 1995 to 2012, 11 of the species that were rare in 1995 were more abundant in 2012 and nine species that were more abundant in 1995 became rare in 2012. Nine species rare in 1995 were not recorded again in any habitat, with new 15 species recorded in 2012 that were not present in any other habitat in 1995 (Table 6). For the grasslands, the number of rare species decreased from 1995 to 2012 of which 33 species were not recorded again in any habitat in 2012. Sixteen species were still rare with seven species increasing in abundance in 2012. Twenty-one of the species that were abundant in 1995 became rare in 2012 (Table 6). In the woody sites, the number of rare species was only slightly less in 2012. Twenty-one species recorded in 1995 was not recorded again for any habitat in 2012, with six rare species increasing in abundance in 2012. Eighteen species were rare in both 1995 and 2012, with 19 species becoming rare in 2012 that were abundant in 1995.

The distribution of the dominant species indicate that species occurring in more than 50% of the vacant lots decreased from 1995 to 2012 with five shared species (Table 7). The dominant species in the grasslands decreased drastically with five shared species, whereas the dominant species in the woody sites increased drastically with seven shared species (Table 7). The Bray-Curtis similarity values indicate that the vacant lot species composition considerably changed from 1995 to 2012 with a similarity of only 32%, the grasslands and the woody sites were more alike but still scored less than 50% similarity (Table 8). However, an analysis of the percentage shared perennial species indicates that the vacant lots became more diverse, with the grasslands and the woody sites respectively becoming more homogeneous (Table 8).

Table 6 Rare species recorded in only one site per habitat. The amount of species absent from the rare species in the other sampling period is listed. The number in brackets indicate species not found in either of the other habitats in that year, e.g. if absent in 2012 from vacant lots, it is the number of species that were not found either in the grasslands or woody sites in 2012. Species that are still rare in the subsequent sampling period (1=1) as well as those that were found in more than 1 site in 2012 (>1 in 2012) or that were more abundant in 1995 (>1 in 1995) are also listed.

	NR only in 1 site	Absent in 2012	1=1	>1 in 2012
Vacant lots 1995	30	15 (9)	4	11
Grasslands in 1995	68	45 (33)	16	7
Woody in 1995	67	43 (21)	18	6

		Absent in 1995		>1 in 1995
Vacant lots in 2012	56	43 (15)	4	9
Grasslands in 2012	58	21 (12)	16	21
Woody in 2012	61	24 (14)	18	19

Table 7 Dominant species found in ≥ 50% of the sites in each habitat for 1995 and 2012 as well as the shared number of species.

	> 50% in 1995	> 50% in 2012	Shared species
Vacant lots	10	9	5
Grasslands	15	8	5
Woody	10	16	7

Table 8 Summary table for all mean diversity value changes per plot. Asterisks indicates significance ($p < 0.05$)

Indicator	Vacant lots	Grasslands	Woody
Bray-Curtis similarity all species	31.7	46.1	46.9
1995 % Shared Perennials	55%	56%	45%
2012 % Shared Perennials	25%	62%	63%
Indigenous Species Richness	↗*	↘*	↘*
Exotic Species Richness	↗*	↘*	=
Disturbed Species Richness	↗	↘*	↘*

The changes in life forms of the woody species indicate that in all except two species the number of trees documented declined from 1995 to 2012. The shrub form accordingly increased for all species, except in the case of *Searsia pyroides,* which decreased with many shrubs maturing into trees as evident from the fact that no trees were recorded in 1995 (Table 9).

Table 9 All species where both trees and shrub forms were observed, indicating changes in structure over the 17 years.

Species	1995 Tree	2012 Tree	Δ	1995 Shrub	2012 Shrub	Δ
Vachellia karroo (Hayne) Banfi & Galasso	18	14	↘	14	26	↗
Celtis africana Burm.f.	16	11	↘	0	10	↗
Senegalia caffra (Thunb.) P.J.H.Hurter & Mabb.	14	11	↘	4	9	↗
Searsia leptodictya Diels	14	10	↘	0	2	↗
Euclea undulata Thunb.	12	5	↘	0	3	↗
Dombeya rotundifolia (Hochst.) Planch. var. rotundifolia	8	6	↘	0	3	↗
Searsia lancea L.f.	4	3	↘	0	4	↗
*Melia azedarach L.**	2	5	↗	0	3	↗
*Robinia pseudoacacia L.**	2	0	↘	0	2	↗
Searsia pyroides (Burch.) Moffett	0	5	↗	11	10	↘

4. Discussion

4.1. Vacant lots

Over the 17-year period, the vacant lots increased radically in their overall species richness with 24 additional indigenous species and 28 additional exotic species. The mean exotic species increased from eight to 17 per site in 2012, with similar patterns found in the indigenous species that increased from nine to 15 mean species per site. Thus for the vacant lots opportunistic indigenous and exotic species invaded in an almost equal measure over the 17-year period. The vacant lots still contained more native species than exotics, but this decreased from 59% in 1995 to 54% in 2012. A study in Ensenada, Mexico also recorded 59% exotic species in its vacant lots (Garcillán et al., 2009). The 1995 cluster analysis (Fig. 3) indicated that despite two sites of higher quality grouping with grassland sites, all the vacant lots had distinctly different species compositions from the grassland and woody sites, also shown in the ANOVA 1995 ISR results (Table 3). On the other hand, in 2012 the ISR values did not differ significantly from the grassland sites and the effect is clearly visible in the cluster analysis (Fig. 4) where many of the grasslands now group with the vacant lots. The possible combined effect of increases in ISR of the vacant lots and significant decreases in the ISR of grassland site may be responsible for this phenomenon. The average DSR was the highest in the vacant lots for all years (Table 5) which is consistent with the fact that vacant lots are much more disturbed habitats. In 1995 only 30 species were found in only one site, compared to the 68 and 67 for the woody and grassland sites, of the 30 species only nine were not recorded again in any habitat in 2012. Eleven of these species increased in abundance over time, only four species recorded again were still rare in 2012. However, in the 2012 vacant lots the rare species increased to 56 of which only 13 were not recorded in the other habitats in 1995. This indicates that the other 28 species absent in the 1995 vacant lots may have spread from other surrounding habitat types (Table 6). The decrease in the number of dominant species indicates the enhanced diversity of the vacant lots (Table 7). There were no apparent differences in the behaviour of the fragmented natural area vacant lots compared with the previously developed vacant lots. The vacant lots were the most dynamic habitat in the 17-year period indicated by the 32% Bray-Curtis similarity values and the only 25% shared perennials per site in 2012. This indicates that for this study vacant lots are not homogenizing over time as predicted for many urban species by McKinney (2006).

4.2. Grasslands

The overall decrease in species richness and especially the indigenous species richness from 186 in 1995 to 138 in 2012 is distressing. The mean ISR per site decreased significantly (Table 4) from 33 to 23 (Table 5) in 2012. The maximum ISR for a site decreased from 62 in 1995 to only 36 in 2012. However, the significant loss of DSR in the midst of the ISR loss needs further investigation into the specific mechanisms involved. ESR also decreased significantly, which is consistent with the findings of du Toit (2009) in Klerksdorp, South Africa that the urbanization gradient is a loss of indigenous species and not the increase of exotic species in remnant natural vegetation in urban areas. The cluster analyses reflect this trend with the fact that in 2012 fewer grasslands grouped together and more sites were more similar to either vacant lots or woody sites. The seven sites that grouped with the vacant lots in the 2012 cluster analysis (Fig. 4) are the grassland sites with the lowest ISR (7 - 20) of all the grassland sites (ISR 22 - 36 per site). These seven sites had a lower mean ISR (12) per site than the mean of 15 of the 2012 vacant lot ISR values. Additionally, these were also the lowest lying grassland sites reciprocating the findings that the 2012 ISR models in paper 2 (of this thesis) showed that increases in altitude predicted higher ISR values. Of the 68 rare species in 1995, 33 were not recorded again in any site of 2012 with only seven species increasing in abundance in 2012. Twenty-one of the species recorded as rare in 2012 were more abundant in 1995 (Table 6). The Bray-Curtis similarity value of 46% together with the fact that 28 of the overall 39 species not recorded again for all habitats were found in only one plot indicates that many of the lost species are rare. Moreover, the percentage shared perennials between the 2012 sites increased to 62%. The number of dominant species per site decreasing from 15 to eight is one factor not advocating homogenization of the sites; all the rest, however, point to this potential outcome. The results of the study in paper 2 (of this thesis) indicated that there were no time lags in the response of grassland sites to the urbanization history. This could mean that grasslands respond more rapidly towards disturbance and fragmentation, and that species are lost at faster rates (see Adriaens et al., 2006). Additional evidence for this might be that the average grassland ISR decreased by ten species, with woody sites decreasing by only five species over the 17-year period.

4.3. Woody communities

The total species richness of the woody sites decreased from 207 to 178 species (Table 2). Over the 17-year period, the ISR declined with 34 species. The mean ISR per plot decreased significantly (Table 4) from 28 to 23 per plot in 2012. However, in 2012 the woody vegetation include the site with the highest maximum ISR value (42).The cluster analyses indicated that the woody sites consistently formed their own distinct grouping. The site (WT74) clustered with the vacant lots had below average ISR (20 vs. group mean of 23) and above average ESR (9 vs. group mean of 4) values (Table 5). Of the 67 rare species in 1995, 21 were not recorded again, 18 were still rare in 2012 and six species increased in abundance. Conversely, 19 of the species that were rare in 2012 were more abundant in 1995. The dominant species occurring in more than 50% of the sites in the woody sites were the only species to increase from ten species in 1995 to 16 species in 2012, of these seven are shared species. This indicates that less common species in 1995 became dominant in 2012. The indigenous annual ruderal herbaceous species, *Pseudognaphalium* sp. were not recorded in 1995 and in 2012 it occurred in 20 sites, additionally the exotic annual weed *Conyza bonariensis* increased from two sites in 1995 to 17 in 2012. These species indicate increases in disturbances in the sites. However, overall the DSR values decreased from eight to six mean species per plot. Results of paper 2 (of this thesis) indicated that woody ISR patterns best responded to past landscape configurations corresponding to major urban development periods (Fig. 1). Average time lags of 20 years were calculated for the ISR with an average time lag of 38 years for the DSR patterns. The models indicated that lower lying sites nearer to the urban areas had higher ISR values. These sites had higher quality vegetation composition; however, their proximity to urban areas put them at risk for further future impacts and fragmentation. The results of the life form changes from dominant tree forms to increases in shrub forms indicated the impact of firewood collection and other disturbances on the woody vegetation (Table 9). The continued harvesting of firewood despite large scale electricity availability was also documented for other areas in South Africa (Madubansi and Shackleton, 2007). *Euclea undulata* decreased from 12 sites with trees to only five sites with trees in 2012. *Celtis africana* had no shrub forms in 1995, but in 2012 ten sites had shrub forms of this species. Moreover, in 1995 only 14 sites had *Vachellia karroo* sites, in 2012 this almost doubled. Although naturally occurring in this area, *Vachellia karroo* is a common bush encroacher (O'Connor, 1995). Although this was not specifically tested for in this study, these trends need to be investigated in more detail.

5. Conclusion

This study was the first long-term urban vegetation study in South Africa and one of the few conducted in temperate natural grassland settings. The observed indigenous species richness declines are disheartening but were also observed for other urban areas (Chocholoušková and Pyšek, 2003; Tait et al., 2005; Williams et al., 2006; Stehlik et al., 2007). The results of this study provides additional evidence for the importance of the incorporation of specific temporal site history (Ramalho and Hobbs, 2012) in the explanation of the differences and similarities in the observed vegetation patterns of sites in urban areas. The presence of time lags (as indicated in paper 2 of this thesis) coupled with the significant decreases in indigenous species richness of woody and grassland sites have important consequences for urban grassland conservation in South Africa. However, in this study we did not explicitly determine the effect of climate on the species richness patterns. Examination of the average monthly rainfall patterns (Fig 2.) indicate that in the 1995 sampling period there was higher average rainfall per month which could also account for recorded higher species diversity in the 1995 sampling period. Additionally, we did not directly quantify fragmentation effects which also negatively affects species composition and is possibly one of the main drivers of the observed species patterns and species declines (Ewers and Didham, 2006; Helm et al., 2006; Krauss et al., 2010; Zipperer et al., 2012). Follow-up monitoring studies will be essential to determine future urbanization impacts and to confirm the observed trends.

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Supplementary Table S1: List of the 49 disturbance indicator species. Exotic species are indicated by an asterisk (*).

Species	**Origin**	**Lifespan**	**Lifeform**	**Reference**
*Alternanthera pungens Kunth**	exotic	perennial	herb	(Louw, 1951; Cilliers et al., 1999)
*Amaranthus hybridus L.**	exotic	annual	herb	(Cilliers and Bredenkamp, 1999)
Aristida canescens Henrard subsp. *canescens*	indigenous	perennial	grass	(Bezuidenhout and Bredenkamp, 1991b; Bredenkamp et al., 1994)
Aristida congesta Roem. & Schult. subsp. *congesta*	indigenous	annual	grass	(Louw, 1951; Bredenkamp et al., 1989; Bezuidenhout and Bredenkamp, 1990, 1991b; Bezuidenhout et al., 1994a, c; Bredenkamp et al., 1994; Cilliers and Bredenkamp, 1999)
Asparagus laricinus Burch.	indigenous	perennial	shrub	(Bredenkamp et al., 1989; Bezuidenhout and Bredenkamp, 1990; Bredenkamp et al., 1994; Cilliers et al., 1999)
Asparagus suaveolens Burch.	indigenous	perennial	shrub	(Bredenkamp et al., 1989; Bezuidenhout and Bredenkamp, 1990, 1991a; Bredenkamp et al., 1994; Cilliers and Bredenkamp, 1999; Cilliers et al., 1999; Daemane et al., 2012)
Atriplex semibaccata R.Br. var. *typica Aellen**	exotic	annual	herb	(Cilliers et al., 1999)
*Bidens bipinnata L.**	exotic	annual	herb	(Bredenkamp et al., 1994; Cilliers and Bredenkamp, 1999; Cilliers et al., 1999)
Blepharis integrifolia (L.f.) E.Mey. ex Schinz var. *integrifolia*	indigenous	perennial	herb	(Louw, 1951)
*Boerhavia erecta L.**	exotic	annual	herb	(van Wyk et al., 1997)
Chamaecrista mimosoides (L.) Greene	indigenous	annual	herb	(Louw, 1951)
Chenopodium mucronatum Thunb.	indigenous	annual	herb	(Cilliers and Bredenkamp, 1999)
Chloris virgata Sw.	indigenous	annual	grass	(Louw, 1951; Cilliers et al., 1999)
Commelina africana L.	indigenous	perennial	herb	(van Wyk et al., 1997; Cilliers et al., 1999)
Conyza podocephala DC.	indigenous	perennial	herb	(Bredenkamp et al., 1994)
Corchorus asplenifolius Burch.	indigenous	perennial	herb	(Louw, 1951)
Cynodon dactylon (L.) Pers.	indigenous	perennial	grass	(Louw, 1951; Bredenkamp et al., 1989; Bezuidenhout and Bredenkamp, 1990, 1991b, a; Bezuidenhout et al., 1994a; Bredenkamp et al., 1994; van Wyk et al., 1997; Cilliers and Bredenkamp, 1999; Cilliers et al., 1999)
Eragrostis gummiflua Nees	indigenous	perennial	grass	(Bezuidenhout et al., 1994a)
Eragrostis lehmanniana Nees var. *lehmanniana*	indigenous	perennial	grass	(Cilliers and Bredenkamp, 1999; Cilliers et al., 1999)
Eragrostis obtusa Munro ex Ficalho & Hiern	indigenous	perennial	grass	(Bredenkamp et al., 1989)
Eragrostis superba Peyr.	indigenous	perennial	grass	(Bezuidenhout et al., 1994a)
Eragrostis trichophora Coss. & Durieu	indigenous	perennial	grass	(Cilliers et al., 1999)

*Euphorbia hirta L.**	exotic	annual	herb	(Cilliers et al., 1999)
Euphorbia inaequilatera Sond. var. *inaequilatera*	indigenous	annual	herb	(Louw, 1951)
Gomphocarpus fruticosus (L.) Aiton f.	indigenous	perennial	shrub	(Louw, 1951)
*Gomphrena celosioides Mart.**	exotic	perennial	herb	(Cilliers et al., 1999)
*Guilleminea densa (Willd. ex Roem. & Schult.) Moq.**	exotic	perennial	herb	(Cilliers et al., 1999)
Ipomoea oblongata E.Mey. ex Choisy	indigenous	perennial	herb	(Louw, 1951)
Ipomoea obscura (L.) Ker Gawl. var. *obscura*	indigenous	perennial	herb	(Louw, 1951)
Ipomoea oenotheroides (L.f.) Raf. ex Hallier f.	indigenous	perennial	shrub	(Louw, 1951)
Mundulea sericea (Willd.) A.Chev.	indigenous	perennial	shrub	(Daemane et al., 2010, 2012)
*Oenothera tetraptera Cav.**	exotic	perennial	herb	(Louw, 1951)
*Opuntia ficus-indica (L.) Mill.**	exotic	perennial	shrub	(Bredenkamp et al., 1994)
Pavonia burchellii (DC.) R.A.Dyer	indigenous	perennial	shrub	(Bezuidenhout et al., 1994b)
*Physalis viscosa L.**	exotic	perennial	herb	(van Wyk et al., 1997; Cilliers and Bredenkamp, 1999)
*Schkuhria pinnata (Lam.) Cabrera**	exotic	annual	herb	(Louw, 1951; Bredenkamp et al., 1994; Cilliers et al., 1999)
Seriphium plumosum L.	indigenous	perennial	shrub	(Louw, 1951; Bredenkamp et al., 1994; Daemane et al., 2012)
Setaria verticillata (L.) P.Beauv.	indigenous	annual	grass	(Cilliers and Bredenkamp, 1999)
Sida spinosa L. var. *spinosa*	indigenous	annual	herb	(Cilliers and Bredenkamp, 1999)
Solanum panduriforme E.Mey.	indigenous	perennial	herb	(Louw, 1951; Cilliers and Bredenkamp, 1999; Cilliers et al., 1999)
*Solanum sisymbriifolium Lam.**	exotic	perennial	herb	(Cilliers et al., 1999)
*Tagetes minuta L.**	exotic	annual	herb	(Louw, 1951; van Wyk et al., 1997; Cilliers and Bredenkamp, 1999; Cilliers et al., 1999)
*Tragopogon dubius Scop.**	exotic	perennial	herb	(Cilliers et al., 1999)
Tragus berteronianus Schult.	indigenous	annual	grass	(Louw, 1951; Bredenkamp et al., 1989; Bezuidenhout and Bredenkamp, 1991b; Bredenkamp et al., 1994; Cilliers et al., 1999)
Tribulus terrestris L.	indigenous	annual	herb	(Louw, 1951; Bredenkamp et al., 1994)
Urochloa mosambicensis (Hack.) Dandy	indigenous	perennial	grass	(Cilliers et al., 1999)
Urochloa panicoides P. Beauv.	indigenous	annual	grass	(Cilliers and Bredenkamp, 1999)
*Verbena aristigera S.Moore**	exotic	perennial	herb	(Cilliers and Bredenkamp, 1999)
*Verbena bonariensis L.**	exotic	annual	herb	(Cilliers and Bredenkamp, 1999)

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Supplementary Table S2: The complete list of the 372 species of the 67 resampled natural areas and vacant lot sites as recorded in 1995 and 2012. Plant names according to Germishuizen et al. (2006), excluding recent *Acacia* and *Rhus* name changes. Listed is the occurrence per site. Highlighted in grey are the species recorded in 2012 not present in the 1995 vacant lot (VL) and natural area (N) resampled list.

				1995		**2012**	
All species	**origin**	**lifespan**	**lifeform**	**N**	**VL**	**N**	**VL**
Abutilon sonneratianum (Cav.) Sweet	indigenous	perennial	shrub	4	0	3	0
Acalypha angustata Sond.	indigenous	perennial	herb	17	0	7	0
Achyranthes aspera L.*	exotic	perennial	herb	5	0	6	0
Aerva leucura Moq.	indigenous	perennial	herb	9	0	5	0
Ailanthus altissima (Mill.) Swingle*	exotic	perennial	shrub	0	2	0	1
Alcea rosea L.*	exotic	perennial	herb	0	0	0	1
Aloe greatheadii Schonland var. *davyana* (Schönland) Glen & D.S.Hardy	indigenous	perennial	herb	32	0	35	1
Alternanthera pungens Kunth*	exotic	perennial	herb	6	11	2	8
Amaranthus hybridus L.*	exotic	annual	herb	0	2	1	5
Ambrosia psilostachya DC.*	exotic	perennial	herb	1	1	1	3
Ammi majus L. var. *glaucifolium* (L.) Godr.*	exotic	annual	herb	0	0	0	1
Ancylobotrys capensis (Oliv.) Pichon	indigenous	perennial	shrub	1	0	0	0
Andropogon schirensis A.Rich.	indigenous	perennial	grass	1	0	0	0
Anisodontea capensis (L.) Bates	indigenous	perennial	shrub	0	0	0	5
Anredera cordifolia (Ten.) Steenis*	exotic	perennial	herb	0	0	0	1
Antizoma angustifolia (Burch.) Miers ex Harv.	indigenous	perennial	herb	7	0	8	0
Aptosimum elongatum Engl.	indigenous	perennial	herb	1	0	1	0
Araujia sericifera Brot.*	exotic	perennial	herb	1	0	3	0
Argemone mexicana L. forma *mexicana**	exotic	annual	herb	0	7	0	1
Aristida adscensionis L.	indigenous	annual	grass	1	0	0	0
Aristida bipartita (Nees) Trin. & Rupr.	indigenous	perennial	grass	3	0	3	0
Aristida canescens Henrard subsp. *canescens*	indigenous	perennial	grass	11	1	8	0
Aristida congesta Roem. & Schult. subsp. *congesta*	indigenous	annual	grass	23	2	8	4
Aristida diffusa Trin. subsp. *burkei* (Stapf) Melderis	indigenous	perennial	grass	1	0	2	0
Aristida stipitata Hack.	indigenous	perennial	grass	0	0	1	0
Arundo donax L.*	exotic	perennial	grass	0	0	0	1
Asparagus africanus Lam.	indigenous	perennial	shrub	7	0	7	0
Asparagus laricinus Burch.	indigenous	perennial	shrub	17	0	19	2
Asparagus suaveolens Burch.	indigenous	perennial	shrub	18	0	21	0
Atriplex semibaccata R.Br. var. *typica* Aellen*	exotic	annual	herb	5	8	2	8
Becium angustifolium (Benth.) N.E.Br.	indigenous	perennial	herb	2	0	1	0
Berkheya radula (Harv.) De Wild.	indigenous	perennial	herb	5	1	3	1
Bewsia biflora (Hack.) Gooss.	indigenous	perennial	grass	2	0	0	0
Bidens bipinnata L.*	exotic	annual	herb	25	4	21	10
Bidens pilosa L.*	exotic	annual	herb	0	0	4	0
Blepharis integrifolia (L.f.) E.Mey. ex Schinz var. *integrifolia*	indigenous	perennial	herb	8	0	6	0
Blepharis serrulata (Nees) Ficalho & Hiern	indigenous	perennial	herb	9	0	3	0
Boerhavia erecta L.*	exotic	annual	herb	0	8	0	2
Bonatea speciosa (L.f.) Willd.	indigenous	perennial	herb	0	0	2	0

Boophone disticha (L.f.) Herb.	indigenous	perennial	herb	5	0	0	0
Boscia albitrunca (Burch.) Gilg & Gilg-Ben.	indigenous	perennial	tree	6	0	6	0
Brachiaria nigropedata (Ficalho. & Hiern) Stapf	indigenous	perennial	grass	10	0	14	0
Brachiaria serrata (Thunb.) Stapf	indigenous	perennial	grass	5	0	9	0
Bromus catharticus Vahl*	exotic	annual	grass	0	0	0	1
Bulbine abyssinica A.Rich.	indigenous	perennial	herb	2	0	1	1
Bulbine narcissifolia Salm-Dyck	indigenous	perennial	herb	3	0	3	0
Bulbostylis burchellii (Ficalho & Hiern) C.B.Clarke	indigenous	perennial	herb	6	0	4	0
Celtis africana Burm.f.	indigenous	perennial	tree	16	0	13	0
Celtis sinensis Pers.*	exotic	perennial	tree	0	0	0	1
Cenchrus ciliaris L.	indigenous	perennial	grass	1	0	0	0
Cestrum aurantiacum Lindl.*	exotic	perennial	shrub	0	0	0	3
Chaetacanthus costatus Nees	indigenous	perennial	herb	7	0	5	0
Chamaecrista biensis (Steyaert) Lock	indigenous	perennial	herb	11	0	2	0
Chamaecrista comosa E.Mey.	indigenous	perennial	herb	1	0	0	0
Chamaecrista mimosoides (L.) Greene	indigenous	annual	herb	1	0	1	0
Chascanum adenostachyum (Schauer) Moldenke	indigenous	perennial	herb	4	0	4	0
Chascanum hederaceum (Sond.) Moldenke	indigenous	perennial	herb	12	0	3	0
Cheilanthes viridis (Forssk.) Sw.	indigenous	perennial	herb	3	0	1	0
Chenopodium album L.*	exotic	annual	herb	0	8	0	6
Chenopodium mucronatum Thunb.	indigenous	annual	herb	14	0	7	0
Chloris pycnothrix Trin.	indigenous	annual	grass	2	2	0	2
Chloris virgata Sw.	indigenous	annual	grass	3	7	1	3
Chlorophytum angulicaule (Baker) Kativu	indigenous	perennial	herb	1	0	1	0
Chlorophytum cooperi (Baker) Nordal	indigenous	perennial	herb	1	0	0	0
Cichorium intybus L. subsp. *intybus**	exotic	perennial	herb	0	2	1	11
Cirsium vulgare (Savi) Ten.*	exotic	annual	herb	0	0	2	0
Citrus limon (L.) Burm.f.*	exotic	perennial	shrub	0	0	0	1
Clematis brachiata Thunb	indigenous	perennial	shrub	17	0	9	0
Cleome rubella Burch.	indigenous	annual	herb	2	0	0	0
Commelina africana L.	indigenous	perennial	herb	19	0	20	0
Commelina benghalensis L.	indigenous	annual	herb	3	1	3	8
Convolvulus arvensis L.*	exotic	perennial	herb	0	0	1	1
Convolvulus saggitatus Thunb.	indigenous	perennial	herb	5	5	4	6
Conyza bonariensis (L.) Cronquist*	exotic	annual	herb	3	12	22	13
Conyza podocephala DC.	indigenous	perennial	herb	9	3	10	7
Corchorus asplenifolius Burch.	indigenous	perennial	herb	15	2	5	2
Coreopsis lanceolata L.*	exotic	perennial	herb	0	0	0	2
Crabbea acaulis N.E.Br.	indigenous	perennial	herb	2	2	2	2
Crabbea angustifolia Nees	indigenous	perennial	herb	9	0	2	0
Crassula capitella Thunb.	indigenous	perennial	herb	5	0	5	0
Crotalaria lotoides Benth.	indigenous	perennial	herb	2	0	0	0
Crotalaria monophylla Germish.	indigenous	perennial	herb	1	0	0	0
Crotalaria virgulata Klotzsch subsp. *grantiana* (Harv.) Polhill	indigenous	annual	herb	3	0	0	0
Cryptolepis oblongifolia (Meisn.) Schltr	indigenous	perennial	shrub	0	0	1	0
Cucumis zeyheri Sond.	indigenous	perennial	herb	0	1	1	0

Cuscuta campestris Yunck.*	exotic	annual	herb	2	0	2	0
Cyanotis speciosa (L.f.) Hassk.	indigenous	perennial	herb	9	0	1	0
Cymbopogon caesius (Hook. & Arn.) Stapf *	indigenous	perennial	grass	0	0	11	0
Cymbopogon pospischilii (K.Schum.) C.E. Hubb.	indigenous	perennial	grass	18	1	8	1
Cynodon dactylon (L.) Pers.	indigenous	perennial	grass	22	15	25	13
Cynodon hirsutus Stent	indigenous	perennial	grass	0	0	0	1
Cyperus sp.	indigenous	perennial	herb	3	1	0	2
Cyphia assimilis Sond.	indigenous	perennial	herb	1	0	0	0
Datura ferox L.*	exotic	annual	herb	0	0	0	1
Datura stramonium L.*	exotic	annual	herb	0	0	0	2
Delosperma herbeum (N.E.Br.) N.E.Br.	indigenous	perennial	herb	7	0	8	0
Deverra burchellii (DC.) Eckl. & Zeyh.	indigenous	perennial	herb	2	0	1	0
Dianthus mooiensis F.N.Williams	indigenous	perennial	herb	1	0	0	0
Dicerocaryum eriocarpum (Decne.) Abels	indigenous	perennial	herb	0	0	1	0
Dichilus lebeckioides DC.	indigenous	perennial	herb	1	0	0	0
Dichondra micrantha Urb.*	exotic	perennial	herb	0	0	2	9
Dicoma anomala Sond.	indigenous	perennial	herb	3	0	2	0
Dicoma macrocephala DC.	indigenous	perennial	herb	2	0	0	0
Digitaria eriantha Steud.	indigenous	perennial	grass	21	0	21	5
Digitaria ternata (A.Rich.) Stapf	indigenous	annual	grass	1	0	1	1
Diheteropogon amplectens (Nees) Clayton	indigenous	perennial	grass	12	0	11	0
Diospyros lycioides Desf. subsp. *guerkei* (Kuntze) De Winter	indigenous	perennial	shrub	3	0	2	0
Dombeya rotundifolia (Hochst.) Planch. var. *rotundifolia*	indigenous	perennial	tree	8	0	8	0
Drimia multisetosa (Baker) Jessop	indigenous	perennial	herb	0	2	0	2
Ehretia rigida (Thunb.) Druce	indigenous	perennial	shrub	17	0	14	0
Elephantorrhiza elephantina (Burch.) Skeels	indigenous	annual	shrub	7	0	5	0
Elionurus muticus (Spreng.) Kuntze	indigenous	perennial	grass	8	1	14	0
Enneapogon cenchroides (Roem. & Schult.) C.E.Hubb.	indigenous	annual	grass	4	5	1	1
Enneapogon scoparius Stapf	indigenous	perennial	grass	2	0	3	0
Eragrostis barbinodis Hack.	indigenous	perennial	grass	2	0	0	0
Eragrostis chloromelas Steud.	indigenous	perennial	grass	23	2	27	11
Eragrostis gummiflua Nees	indigenous	perennial	grass	3	0	2	1
Eragrostis lehmanniana Nees var. *lehmanniana*	indigenous	perennial	grass	12	6	5	1
Eragrostis micrantha Hack.	indigenous	perennial	grass	1	0	0	0
Eragrostis obtusa Munro ex Ficalho & Hiern	indigenous	perennial	grass	11	2	1	2
Eragrostis plana Nees	indigenous	perennial	grass	2	5	1	5
Eragrostis racemosa (Thunb.) Steud.	indigenous	perennial	grass	14	0	9	0
Eragrostis superba Peyr.	indigenous	perennial	grass	16	1	3	2
Eragrostis trichophora Coss. & Durieu	indigenous	perennial	grass	10	2	4	3
Eucalyptus camaldulensis Dehnh.*	exotic	perennial	shrub	0	0	1	0
Euclea crispa (Thunb.) Gürke subsp. *crispa*	indigenous	perennial	shrub	1	0	0	0
Euclea undulata Thunb.	indigenous	perennial	tree	12	0	7	0
Euphorbia heterophylla L.*	exotic	annual	herb	0	0	0	1
Euphorbia hirta L.*	exotic	annual	herb	3	0	0	1
Euphorbia inaequilatera Sond. var. *inaequilatera*	indigenous	annual	herb	16	1	2	1
Euphorbia prostrata Aiton*	exotic	annual	herb	0	0	0	2

Eustachys paspaloides (Vahl) Lanza & Mattei	indigenous	perennial	grass	15	0	4	0
Falkia oblonga Bernh. ex C.Krauss	indigenous	perennial	shrub	1	2	1	0
Felicia muricata (Thunb.) Nees subsp. *muricata*	indigenous	perennial	herb	9	5	12	5
Flaveria bidentis (L.) Kuntze*	exotic	annual	herb	1	0	0	0
Foeniculum vulgare Mill. var. *vulgare**	exotic	perennial	herb	0	0	0	2
Galium spurium L. subsp. *africanum* Verdc.	indigenous	annual	herb	1	0	0	0
Gazania krebsiana Less. subsp. *serrulata* (DC.) Roessler	indigenous	perennial	herb	1	0	0	0
Gladiolus crassifolius Baker	indigenous	perennial	herb	2	0	1	0
Gladiolus permeabilis D.Delaroche subsp. *edulis* (Burch. ex Ker Gawl.) Oberm.	indigenous	perennial	herb	3	0	1	0
Gnidia caffra (Meisn.) Gilg	indigenous	perennial	shrub	7	0	2	0
Gnidia capitata L.f.	indigenous	perennial	shrub	2	0	3	0
Gnidia sericocephala (Meisn.) Gilg ex Engl.	indigenous	perennial	shrub	2	0	2	0
Gomphocarpus fruticosus (L.) Aiton f.	indigenous	perennial	shrub	1	1	0	0
Gomphrena celosioides Mart.*	exotic	perennial	herb	10	2	3	5
Grewia flava DC.	indigenous	perennial	shrub	24	0	19	0
Grewia occidentalis L. var. *occidentalis*	indigenous	perennial	shrub	5	0	4	0
Guilleminea densa (Willd. ex Roem. & Schult.) Moq.*	exotic	perennial	herb	3	5	4	4
Gymnosporia buxifolia (L.) Szyszyl.	indigenous	perennial	shrub	6	0	8	0
Gynmosporia tenuispina (Sond.) Szyszyl.	indigenous	perennial	shrub	0	0	1	0
Haplocarpha lyrata Harv.	indigenous	perennial	herb	0	0	1	0
Haplocarpha scaposa Harv.	indigenous	perennial	herb	2	0	0	0
Helichrysum caespititium (DC.) Harv.	indigenous	perennial	herb	1	0	0	0
Helichrysum nudifolium (L.) Less. var. *nudifolium*	indigenous	perennial	herb	6	0	5	0
Helichrysum rugulosum Less.	indigenous	perennial	herb	0	0	5	1
Helichrysum setosum Harv.	indigenous	perennial	herb	2	0	2	0
Helichrysum zeyheri Less.	indigenous	perennial	herb	1	0	0	0
Hermannia depressa N.E.Br	indigenous	perennial	herb	9	2	10	4
Heteropogon contortus (L.) Roem. & Schult.	indigenous	perennial	grass	26	1	17	0
Hibiscus aethiopicus L.	indigenous	perennial	herb	1	0	0	0
Hibiscus engleri K.Schum.	indigenous	perennial	herb	0	0	2	0
Hibiscus pusillus Thunb.	indigenous	perennial	herb	13	3	6	3
Hibiscus trionum L.	indigenous	annual	herb	1	0	0	0
Hyparrhenia hirta (L.) Stapf	indigenous	perennial	grass	12	0	13	6
Hypoxis hemerocallidea Fisch.Mey. & Ave-Lall	indigenous	perennial	herb	5	0	1	1
Hypoxis rigidula Baker	indigenous	perennial	herb	3	0	1	0
Indigofera comosa N.E.Br	indigenous	perennial	shrub	1	0	0	1
Indigofera cryptantha Benth. ex Harv. var. *cryptantha*	indigenous	perennial	shrub	1	1	0	3
Indigofera daleoides Benth. ex Harv. var. *daleoides*	indigenous	perennial	herb	3	0	3	0
Indigofera filipes Benth. ex Harv.	indigenous	perennial	herb	1	0	1	0
Indigofera heterotricha DC.	indigenous	perennial	herb	23	0	20	0
Indigofera oxytropis Benth. ex Harv.	indigenous	perennial	herb	3	0	1	0
Indigofera rhytidocarpa Benth. ex Harv. subsp. *rhytidocarpa*	indigenous	annual	herb	7	2	3	1
Indigofera vicioides Jaub. & Spach var. *vicioides*	indigenous	perennial	herb	0	0	1	0
Ipomoea oblongata E.Mey. ex Choisy	indigenous	perennial	herb	6	0	2	0
Ipomoea obscura (L.) Ker Gawl. var. *obscura*	indigenous	perennial	herb	13	0	8	0

Ipomoea oenotheroides (L.f.) Raf. ex Hallier f.	indigenous	perennial	shrub	1	0	0	0
Ipomoea ommaneyi Rendle	indigenous	perennial	herb	0	0	1	0
Ipomoea purpurea (L.) Roth*	exotic	annual	herb	1	0	1	5
Jamesbrittenia aurantiaca (Burch.) Hilliard	indigenous	perennial	herb	5	0	9	0
Kalanchoe rotundifolia (Haw.) Haw.	indigenous	perennial	shrub	1	0	1	0
Kalanchoe sp.	indigenous	perennial	shrub	0	0	1	0
Kalanchoe thyrsiflora Harv.	indigenous	perennial	shrub	3	0	1	0
Kohautia amatymbica Eckl. & Zeyh.	indigenous	annual	herb	0	0	1	0
Kohautia caespitosa Schnizl. subsp. *brachyloba* (Sond.) D.Mantell	indigenous	annual	herb	1	0	0	0
Kohautia cynanchica DC.	indigenous	annual	herb	1	0	3	0
Kyphocarpa angustifolia (Moq.) Lopr.	indigenous	annual	herb	3	0	0	0
Lactuca inermis Forssk.	indigenous	perennial	herb	2	1	2	6
Lactuca serriola L.*	exotic	perennial	herb	0	8	0	6
Lantana camara L.*	exotic	perennial	shrub	1	0	0	0
Lantana rugosa Thunb.	indigenous	perennial	shrub	1	0	3	0
Ledebouria luteola Jessop	indigenous	perennial	herb	0	1	0	0
Ledebouria ovatifolia (Baker) Jessop	indigenous	perennial	herb	2	0	1	0
Ledebouria revoluta (L.f.) Jessop	indigenous	perennial	herb	10	0	7	1
Lepidium sp.	indigenous	annual	herb	4	13	2	9
Leucas capensis (Benth.) Engl.	indigenous	perennial	shrub	1	0	0	1
Ligustrum lucidum W.T.Aiton*	exotic	perennial	tree	1	0	1	1
Limeum viscosum (J.Gay) Fenzl subsp. *viscosum* var. *glomeratum* (Eckl. & Zeyh.) Friedrich	indigenous	annual	herb	1	0	1	0
Lippia scaberrima Sond.	indigenous	perennial	herb	18	1	12	0
Lotononis calycina (E.Mey.) Benth.	indigenous	perennial	herb	0	0	1	0
Lotononis listii Polhill	indigenous	perennial	herb	3	0	2	2
Loudetia simplex (Nees) C.E.Hubb.	indigenous	perennial	grass	0	0	1	0
Macledium zeyheri (Sond.) S.Ortíz subsp. *zeyheri*	indigenous	perennial	herb	0	0	3	0
Maerua cafra (DC.) Pax	indigenous	perennial	shrub	1	0	0	0
Malva parviflora L. var. *parviflora**	exotic	annual	herb	0	0	0	1
Malvastrum coromandelianum (L.) Garcke*	exotic	perennial	herb	3	3	2	5
Medicago sativa L.*	exotic	perennial	herb	1	0	0	7
Melia azedarach L.*	exotic	perennial	tree	2	2	6	4
Melilotus alba Desr.*	exotic	annual	herb	0	0	2	3
Melinis nerviglumis (Franch.) Zizka	indigenous	perennial	grass	10	0	13	0
Melinis repens (Willd.) Zizka	indigenous	annual	grass	13	0	13	1
Mirabilis jalapa L.*	exotic	perennial	herb	0	0	0	3
Modiola caroliniana (L.) G.Don*	exotic	annual	herb	1	1	0	5
Monsonia angustifolia E.Mey. ex A.Rich.	indigenous	annual	herb	11	0	2	0
Moraea thomsonii Baker	indigenous	perennial	herb	0	0	0	1
Morus alba L. var. *alba**	exotic	perennial	tree	0	0	0	1
Mundulea sericea (Willd.) A.Chev.	indigenous	perennial	shrub	1	0	0	0
Mystroxylon aethiopicum (Thunb.) Loes. subsp. *burkeanum* (Sond.) R.H.Archer	indigenous	perennial	shrub	13	0	9	0
Neorautanenia ficifolius (Benth.) C.A.Sm.	indigenous	perennial	herb	0	0	1	0
Nidorella anomala Steetz	indigenous	annual	herb	1	0	11	2

Nidorella hottentotica DC.	indigenous	annual	herb	2	0	6	0
Nolletia ciliaris (DC.) Steetz	indigenous	perennial	shrub	1	0	0	0
Nolletia rarifolia (Turcz.) Steetz	indigenous	perennial	shrub	1	0	3	0
Nothoscordum gracile (Aiton) Stearn*	exotic	perennial	herb	0	0	0	1
Oenothera tetraptera Cav.*	exotic	perennial	herb	4	0	0	5
Oldenlandia herbacea (L.) Roxb. var. *herbacea*	indigenous	annual	herb	2	0	3	0
Olea europaea L. subsp. *africana* (Mill.) P.S.Green	indigenous	perennial	tree	6	0	3	0
Opuntia ficus-indica (L.) Mill.*	exotic	perennial	shrub	3	0	4	0
Opuntia imbricata (Haw.) DC.*	exotic	perennial	shrub	1	0	4	0
Ornithogalum setosum (Jacq.) J.C. Manning & Goldblatt	indigenous	perennial	herb	5	0	5	0
Ornithogalum sp.	indigenous	perennial	herb	0	0	0	5
Ornithogalum viride (L.) J.C.Manning & Goldblatt	indigenous	perennial	herb	0	0	0	4
Osteospermum muricatum E.Mey. ex DC. subsp. *muricatum*	indigenous	perennial	herb	2	2	1	1
Osyris lanceolata Hochst. & Steud.	indigenous	perennial	shrub	2	0	1	0
Oxalis corniculata L.*	exotic	annual	herb	5	1	1	3
Oxalis obliquifolia Steud. ex Rich.	indigenous	perennial	herb	0	0	0	1
Oxygonum dregeanum Meisn.	indigenous	annual	herb	1	0	0	0
Pachystigma pygmaeum (Schltr.) Robyns	indigenous	perennial	shrub	4	0	0	0
Panicum coloratum L. var. *coloratum*	indigenous	perennial	grass	3	2	5	1
Panicum maximum Jacq	indigenous	perennial	grass	13	0	20	1
Pappea capensis Eckl. & Zeyh.	indigenous	perennial	tree	4	0	2	0
Paspalum dilatatum Poir.*	exotic	perennial	grass	1	0	0	2
Paspalum distichum L.	indigenous	perennial	grass	0	0	0	1
Pavetta zeyheri Sond. subsp. *zeyheri*	indigenous	perennial	shrub	7	0	8	0
Pavonia burchellii (DC.) R.A.Dyer	indigenous	perennial	shrub	4	0	3	0
Pearsonia cajanifolia (Harv.) Polhill subsp. *cajanifolia*	indigenous	perennial	herb	1	0	0	0
Pearsonia uniflora (Kensit) Polhill	indigenous	perennial	herb	1	0	0	0
Pellaea calomelanos (Sw.) Link var. *calomelanos*	indigenous	perennial	herb	11	0	12	0
Pennisetum clandestinum Hochst. ex Chiov.*	exotic	perennial	grass	2	3	3	12
Pentarrhinum insipidum E.Mey.	indigenous	perennial	herb	13	0	17	1
Phyllanthus incurvus Thunb.	indigenous	perennial	herb	1	0	0	0
Phyllanthus maderaspatensis L	indigenous	perennial	herb	9	0	1	0
Phyllanthus parvulus Sond.	indigenous	perennial	herb	0	0	2	0
Physalis viscosa L.*	exotic	perennial	herb	14	4	19	14
Picris echioides L.*	exotic	annual	herb	0	0	0	1
Plantago lanceolata L.*	exotic	perennial	herb	2	1	3	13
Plumbago auriculata Lam.	indigenous	perennial	shrub	6	0	7	0
Pogonarthria squarrosa (Roem. & Schult.) Pilg.	indigenous	perennial	grass	7	0	2	0
Pollichia campestris Aiton	indigenous	perennial	herb	21	0	16	1
Polygala amatymbica Eckl. & Zeyh.	indigenous	perennial	herb	4	0	0	0
Polygala hottentotta C.Presl	indigenous	perennial	herb	1	0	3	0
Portulaca oleracea L.*	exotic	annual	herb	0	2	0	1
Portulaca quadrifida L.	indigenous	annual	herb	0	1	0	0
Prunus armeniaca L.*	exotic	perennial	tree	0	0	1	0
Pseudognaphalium sp.	indigenous	annual	herb	3	0	26	7
Pupalia lappacea (L.) A.Juss. var. *lappacea*	indigenous	annual	herb	4	0	2	0

Pyracantha angustifolia (Franch.) C.K.Schneid.*	exotic	perennial	shrub	3	0	3	0
Ranunculus multifidus Forssk.	indigenous	perennial	herb	1	0	0	0
Raphionacme hirsuta (E.Mey.) R.A.Dyer ex E.Phillips	indigenous	perennial	herb	4	0	0	0
Raphionacme velutina Schltr.	indigenous	perennial	herb	3	0	4	0
Rhynchosia nervosa Benth. & Harv. var. *nervosa*	indigenous	perennial	herb	2	0	1	0
Rhynchosia nitens Benth.	indigenous	perennial	shrub	1	0	1	0
Rhynchosia totta (Thunb.) DC. var. *totta*	indigenous	perennial	herb	6	0	1	0
Rhynchosia venulosa (Hiern) K.Schum.	indigenous	perennial	herb	1	0	0	0
Robinia pseudoacacia L.*	exotic	perennial	tree	2	0	2	1
Salvia runcinata L.f.	indigenous	perennial	herb	3	0	1	4
Salvia splendens Sellow ex Roem. & Schult.*	exotic	perennial	shrub	0	0	0	1
Salvia tiliifolia Vahl*	exotic	annual	herb	1	0	1	0
Sansevieria aethiopica Thunb.	indigenous	perennial	herb	2	0	0	0
Saponaria officinalis L.*	exotic	perennial	herb	0	0	0	1
Scabiosa columbaria L.	indigenous	perennial	herb	3	0	2	0
Schistostephium heptalobum (DC.) Oliv. & Hiern	indigenous	perennial	shrub	1	0	0	0
Schizachyrium sanguineum (Retz.) Alston	indigenous	perennial	grass	11	0	13	0
Schkuhria pinnata (Lam.) Cabrera*	exotic	annual	herb	17	3	4	5
Searsia lancea L.f.	indigenous	perennial	tree	4	0	5	1
Searsia leptodictya Diels	indigenous	perennial	tree	14	0	12	0
Searsia magalismontana (Sond.) Moffett	indigenous	perennial	shrub	12	0	11	0
Searsia pyroides (Burch.) Moffett	indigenous	perennial	tree	11	0	12	0
Searsia rigida (Mill.) F.A.Barkley	indigenous	perennial	shrub	2	0	1	0
Searsia undulata (Jacq.) T.S.Yi , A.J.Mill. & J.Wen	indigenous	perennial	shrub	2	0	0	0
Selago densiflora Rolfe	indigenous	perennial	herb	7	0	2	0
Senecio achilleifolius DC.	indigenous	perennial	herb	1	0	0	0
Senecio coronatus (Thunb.) Harv.	indigenous	perennial	herb	1	0	0	0
Senecio inornatus DC.	indigenous	perennial	herb	3	0	3	0
Senecio oxyriifolius DC. subsp. *oxyriifolius*	indigenous	perennial	herb	1	0	1	0
Senecio venosus Harv.	indigenous	perennial	herb	12	0	7	0
Senegalia caffra (Thunb.) P.J.H.Hurter & Mabb.	indigenous	perennial	tree	18	0	16	0
Senegalia hereroensis (Engl.) Kyal. & Boatwr.	indigenous	perennial	tree	1	0	0	0
Senna didymobotrya (Fresen.) Irwin & Barneby*	exotic	perennial	shrub	0	0	0	1
Seriphium plumosum L.	indigenous	perennial	shrub	2	0	0	0
Setaria incrassata (Hochst.) Hack.	indigenous	perennial	grass	1	0	2	0
Setaria lindenbergiana (Nees) Stapf	indigenous	perennial	grass	0	0	2	0
Setaria nigrirostris (Nees) T.Durand & Schinz	indigenous	perennial	grass	1	0	0	0
Setaria pumila (Poir.) Roem. & Schult.	indigenous	annual	grass	0	0	1	1
Setaria sphacelata (Schumach.) Moss var. *torta* (Stapf) Clayton	indigenous	perennial	grass	24	0	16	0
Setaria verticillata (L.) P.Beauv.	indigenous	annual	grass	3	0	3	3
Sida alba L.	indigenous	annual	shrub	0	0	0	1
Sida rhombifolia L. subsp. *rhombifolia*	indigenous	annual	shrub	2	0	2	0
Sida spinosa L. var. *spinosa*	indigenous	annual	herb	9	2	6	6
Sisymbrium orientale L.*	exotic	annual	herb	0	1	0	0
Solanum elaeagnifolium Cav.*	exotic	perennial	shrub	1	5	2	5
Solanum lichtensteinii Willd.	indigenous	perennial	shrub	4	0	2	0

Solanum mauritianum Scop.*	exotic	perennial	shrub	0	1	0	0
Solanum nigrum L.*	exotic	annual	herb	2	0	1	0
Solanum panduriforme E.Mey.	indigenous	perennial	herb	10	4	3	3
Solanum sisymbriifolium Lam.*	exotic	perennial	herb	1	1	0	3
Solanum supinum Dunal var. *supinum*	indigenous	perennial	shrub	2	0	0	0
Sonchus asper (L.) Hill subsp. *asper**	exotic	annual	herb	0	1	0	0
Sonchus oleraceus L.*	exotic	annual	herb	0	1	0	0
Sorghum halepense (L.) Pers.*	exotic	perennial	grass	0	0	0	1
Sporobolus africanus (Poir.) Robyns & Tournay	indigenous	perennial	grass	1	0	0	0
Sporobolus fimbriatus (Trin.) Nees	indigenous	perennial	grass	7	3	8	2
Stachys hyssopoides Burch. ex Benth.	indigenous	perennial	herb	1	3	1	3
Stachys spathulata Burch. ex Benth.	indigenous	perennial	herb	0	1	0	0
Striga asiatica (L.) Kuntze	indigenous	annual	herb	6	0	1	0
Striga bilabiata (Thunb.) Kuntze subsp. *bilabiata*	indigenous	annual	herb	1	0	0	0
Sutera caerulea (L.f.) Hiern	indigenous	annual	herb	0	0	1	0
Tagetes minuta L.*	exotic	annual	herb	32	2	27	1
Talinum arnotii Hook.f.	indigenous	annual	shrub	5	0	0	0
Talinum caffrum (Thunb.) Eckl. & Zeyh.	indigenous	annual	herb	0	0	1	5
Taraxacum officinale Weber*	exotic	perennial	herb	2	3	0	7
Tarchonanthus camphoratus L.	indigenous	perennial	shrub	1	0	0	0
Tephrosia burchellii Burtt Davy	indigenous	annual	herb	1	0	0	0
Tephrosia capensis (Jacq.) Pers.	indigenous	perennial	herb	1	0	0	0
Tephrosia longipes Meisn. subsp. *longipes* var. *longipes*	indigenous	annual	herb	2	0	1	0
Teucrium trifidum Retz.	indigenous	perennial	herb	14	0	8	0
Themeda triandra Forssk.	indigenous	perennial	grass	37	2	31	3
Thesium sp.	indigenous	perennial	herb	5	2	11	2
Trachyandra sp.	indigenous	perennial	herb	8	0	2	0
Trachypogon spicatus (L.f.) Kuntze	indigenous	perennial	grass	1	0	4	0
Tragia rupestris Sond.	indigenous	perennial	herb	0	0	7	0
Tragopogon dubius Scop.*	exotic	perennial	herb	2	7	2	7
Tragus berteronianus Schult.	indigenous	annual	grass	3	2	1	1
Tribulus terrestris L.	indigenous	annual	herb	2	5	0	3
Trichodesma angustifolium Harv. subsp. *angustifolium*	indigenous	perennial	herb	1	0	0	0
Trichoneura grandiglumis (Nees) Ekman	indigenous	perennial	grass	7	0	2	1
Tripteris aghillana DC. var. *aghillana*	indigenous	perennial	herb	7	0	4	1
Triraphis andropogonoides (Steud.) E.Phillips	indigenous	perennial	grass	11	0	11	0
Tristachya leucothrix Nees	indigenous	perennial	grass	0	0	1	0
Triumfetta sonderi Ficalho & Hiern	indigenous	perennial	shrub	9	0	7	0
Urochloa mosambicensis (Hack.) Dandy	indigenous	perennial	grass	6	2	3	14
Urochloa panicoides P. Beauv.	indigenous	annual	grass	2	9	0	2
Vachellia hebeclada (DC.) Kyal. & Boatwr.	indigenous	perennial	shrub	3	0	1	0
Vachellia karroo (Hayne) Banfi & Galasso	indigenous	perennial	tree	31	2	28	5
Vachellia robusta (Burch.) Kyal. & Boatwr.	indigenous	perennial	tree	12	0	10	0
Vangueria infausta Burch. subsp. *infausta*	indigenous	perennial	shrub	6	0	9	0
Vangueria parvifolia Sond.	indigenous	perennial	tree	3	0	3	0
Verbascum virgatum Stokes*	exotic	perennial	herb	0	1	0	0

Verbena aristigera S.Moore*	exotic	perennial	herb	5	1	2	5
Verbena bonariensis L.*	exotic	annual	herb	6	6	6	6
Verbena officinalis L.*	exotic	annual	herb	0	0	0	7
Vernonia oligocephala (DC.) Sch.Bip. ex Walp.	indigenous	perennial	herb	17	0	17	0
Vernonia poskeana Vatke & Hildebr. subsp. *botswanica* G.V.Pope	indigenous	annual	herb	1	0	0	0
Viscum rotundifolium L.f.	indigenous	perennial	shrub	2	0	0	0
Wahlenbergia undulata (L.f.) A.DC.	indigenous	perennial	herb	4	0	2	0
Xenostegia tridentata (L.) D.F.Austin & Staples subsp. *angustifolia* (Jacq.) Lejoly & Lisowski	indigenous	perennial	herb	2	0	0	0
Xysmalobium undulatum (L.) Aiton f.	indigenous	perennial	herb	2	0	0	0
Zanthoxylum capense (Thunb.) Harv.	indigenous	perennial	shrub	10	0	6	0
Zinnia peruviana (L.) L.*	exotic	annual	herb	3	1	3	0
Ziziphus mucronata Willd. subsp. *mucronata*	indigenous	perennial	tree	1	0	0	0
Ziziphus zeyheriana Sond.	indigenous	perennial	shrub	25	0	18	0
Zornia capensis Pers. subsp. *capensis*	indigenous	perennial	herb	4	0	0	0

References

Germishuizen G, Meyer NL, Steenkamp Y, Keith M (eds) (2006) A checklist of South African plants. Southern African Botanical Diversity Network Reoprt No. 41. SABONET, Pretoria

Supplementary Table S3: List of the 24 declared invasive plants recorded in the study area. Plants listed as declared invaders according to the Conservation of Agricultural Resources Act, 1983 (Act No 43 of 1983) (CARA) amended in 2001 recorded in the 2012 surveys. As per CARA: "*Category 1: Invader plants must be removed and destroyed immediately. No trade in these plants; category 2: invader plants may be grown under controlled conditions in permitted zones. No trade in these plants; category 3: Invader plants may no longer be propagated or sold. Existing plants do not need to be removed*." Plant names according to Germishuizen et al. (2006). Natural areas (N), vacant lots (VL), Conservation of Agricultural Resources Act category (CAT).

				1995		**2012**		
Species	**origin**	**lifespan**	**lifeform**	**N**	**VL**	**N**	**VL**	**CAT**
Achyranthes aspera L.*	exotic	perennial	herb	5	0	6	0	1
Anredera cordifolia (Ten.) Steenis*	exotic	perennial	herb	0	0	0	1	1
Araujia sericifera Brot.*	exotic	perennial	herb	1	0	3	0	1
Argemone mexicana L. forma *mexicana**	exotic	annual	herb	0	7	0	1	1
Arundo donax L.*	exotic	perennial	grass	0	0	0	1	1
Cestrum aurantiacum Lindl.*	exotic	perennial	shrub	0	0	0	3	1
Convolvulus arvensis L.*	exotic	perennial	herb	0	0	1	1	1
Cuscuta campestris Yunck.*	exotic	annual	herb	2	0	2	0	1
Datura ferox L.*	exotic	annual	herb	0	0	0	1	1
Datura stramonium L.*	exotic	annual	herb	0	0	0	2	1
Opuntia imbricata (Haw.) DC.*	exotic	perennial	shrub	1	0	4	0	1
Solanum elaeagnifolium Cav.*	exotic	perennial	shrub	1	5	2	5	1
Cirsium vulgare (Savi) Ten.*	exotic	annual	herb	0	0	2	0	1
Eucalyptus camaldulensis Dehnh.*	exotic	perennial	shrub	0	0	1	0	2
Robinia pseudoacacia L.*	exotic	perennial	tree	2	0	2	1	2
Solanum sisymbriifolium Lam.*	exotic	perennial	herb	1	1	0	3	2
Sorghum halepense (L.) Pers.*	exotic	perennial	grass	0	0	0	1	2
Ailanthus altissima (Mill.) Swingle*	exotic	perennial	shrub	0	2	0	1	3
Ipomoea purpurea (L.) Roth*	exotic	annual	herb	1	0	1	5	3
Ligustrum lucidum W.T.Aiton*	exotic	perennial	tree	1	0	1	1	3
Melia azedarach L.*	exotic	perennial	tree	2	2	6	4	3
Morus alba L. var. *alba**	exotic	perennial	tree	0	0	0	1	3
Pyracantha angustifolia (Franch.) C.K.Schneid.*	exotic	perennial	shrub	3	0	3	0	3
Senna didymobotrya (Fresen.) Irwin & Barneby*	exotic	perennial	shrub	0	0	0	1	3

References

Germishuizen G, Meyer NL, Steenkamp Y, Keith M (eds) (2006) A checklist of South African plants. Southern African Botanical Diversity Network Reoprt No. 41. SABONET, Pretoria

Supplementary Table S4: The 74 species recorded in the resampled sites in 1995 that was absent in 2012. 35 of the species was recorded by other studies as still present in Potchefstroom, of these 6 were recorded in the nearby towns of Orkney and Klerksdorp (du Toit 2009). Plant names according to Germishuizen et al. (2006). Natural areas (N), Vacant lots (VL).

All species	Origin	Lifespan	Life form	N	VL	Reference
Pachystigma pygmaeum (Schltr.) Robyns	indigenous	perennial	shrub	4	0	(Jansen van Rensburg 2010)
Andropogon schirensis A.Rich.	indigenous	perennial	grass	1	0	(Van der Walt 2013)
Aristida adscensionis L.	indigenous	annual	grass	1	0	(Van der Walt 2013)
Boophone disticha (L.f.) Herb.	indigenous	perennial	herb	5	0	(Van der Walt 2013)
Chlorophytum cooperi (Baker) Nordal	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Crotalaria lotoides Benth.	indigenous	perennial	herb	2	0	(Van der Walt 2013)
Dianthus mooiensis F.N.Williams	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Dicoma macrocephala DC.	indigenous	perennial	herb	2	0	(Van der Walt 2013)
Eragrostis micrantha Hack.	indigenous	perennial	grass	1	0	(Van der Walt 2013)
Gazania krebsiana Less. subsp. serrulata (DC.) Roessler	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Gomphocarpus fruticosus (L.) Aiton f.	indigenous	perennial	shrub	1	1	(Van der Walt 2013)
Haplocarpha scaposa Harv.	indigenous	perennial	herb	2	0	(Van der Walt 2013)
Helichrysum caespititium (DC.) Harv.	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Hibiscus aethiopicus L.	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Hibiscus trionum L.	indigenous	annual	herb	1	0	(Van der Walt 2013)
Kohautia caespitosa Schnizl. subsp. brachyloba (Sond.) D.Mantell	indigenous	annual	herb	1	0	(Van der Walt 2013)
Pearsonia cajanifolia (Harv.) Polhill subsp. cajanifolia	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Polygala amatymbica Eckl. & Zeyh.	indigenous	perennial	herb	4	0	(Van der Walt 2013)
Portulaca quadrifida L.	indigenous	annual	herb	0	1	(Van der Walt 2013)
Ranunculus multifidus Forssk.	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Raphionacme hirsuta (E.Mey.) R.A.Dyer ex E.Phillips	indigenous	perennial	herb	4	0	(Van der Walt 2013)
Seriphium plumosum L.	indigenous	perennial	shrub	2	0	(Van der Walt 2013)
Setaria nigrirostris (Nees) T.Durand & Schinz	indigenous	perennial	grass	1	0	(Van der Walt 2013)
*Sonchus oleraceus L.**	exotic	annual	herb	0	1	(Van der Walt 2013)
Stachys spathulata Burch. ex Benth.	indigenous	perennial	herb	0	1	(Van der Walt 2013)
Trichodesma angustifolium Harv. subsp. angustifolium	indigenous	perennial	herb	1	0	(Van der Walt 2013)
Vernonia poskeana Vatke & Hildebr. subsp. botswanica G.V.Pope	indigenous	annual	herb	1	0	(Van der Walt 2013)
Xysmalobium undulatum (L.) Aiton f.	indigenous	perennial	herb	2	0	(Van der Walt 2013)
Ziziphus mucronata Willd. subsp. mucronata (T)	indigenous	perennial	tree	1	0	(Van der Walt 2013)
Helichrysum zeyheri Less.	indigenous	perennial	herb	1	0	(du Toit 2009)
Ipomoea oenotheroides (L.f.) Raf. ex Hallier f.	indigenous	perennial	shrub	1	0	(du Toit 2009)
Kyphocarpa angustifolia (Moq.) Lopr.	indigenous	annual	herb	3	0	(du Toit 2009)
Sporobolus africanus (Poir.) Robyns & Tournay	indigenous	perennial	grass	1	0	(du Toit 2009)

Tephrosia burchellii Burtt Davy	indigenous	annual	herb	1	0	(du Toit 2009)
Tephrosia capensis (Jacq.) Pers.	indigenous	perennial	herb	1	0	(du Toit 2009)
Ancylobotrys capensis (Oliv.) Pichon	indigenous	perennial	shrub	1	0	
Bewsia biflora (Hack.) Gooss.	indigenous	perennial	grass	2	0	
Cenchrus ciliaris L.	indigenous	perennial	grass	1	0	
Chamaecrista comosa E.Mey.	indigenous	perennial	herb	1	0	
Cleome rubella Burch.	indigenous	annual	herb	2	0	
Crotalaria monophylla Germish.	indigenous	perennial	herb	1	0	
Crotalaria virgulata Klotzsch subsp. grantiana (Harv.) Polhill	indigenous	annual	herb	3	0	
Cyphia assimilis Sond.	indigenous	perennial	herb	1	0	
Dichilus lebeckioides DC.	indigenous	perennial	herb	1	0	
Eragrostis barbinodis Hack.	indigenous	perennial	grass	2	0	
Euclea crispa (Thunb.) Gürke subsp. crispa (T)	indigenous	perennial	shrub	1	0	
*Flaveria bidentis (L.) Kuntze**	exotic	annual	herb	1	0	
Galium spurium L. subsp. africanum Verdc.	indigenous	annual	herb	1	0	
*Lantana camara L.**	exotic	perennial	shrub	1	0	
Ledebouria luteola Jessop	indigenous	perennial	herb	0	1	
Maerua cafra (DC.) Pax (S)	indigenous	perennial	shrub	1	0	
Mundulea sericea (Willd.) A.Chev.	indigenous	perennial	shrub	1	0	
Nolletia ciliaris (DC.) Steetz	indigenous	perennial	shrub	1	0	
Oxygonum dregeanum Meisn.	indigenous	annual	herb	1	0	
Pearsonia uniflora (Kensit) Polhill	indigenous	perennial	herb	1	0	
Phyllanthus incurvus Thunb.	indigenous	perennial	herb	1	0	
Rhynchosia venulosa (Hiern) K.Schum.	indigenous	perennial	herb	1	0	
Sansevieria aethiopica Thunb.	indigenous	perennial	herb	2	0	
Schistostephium heptalobum (DC.) Oliv. & Hiern	indigenous	perennial	shrub	1	0	
Searsia undulata (Jacq.) T.S.Yi , A.J.Mill. & J.Wen (S)	indigenous	perennial	shrub	2	0	
Senecio achilleifolius DC.	indigenous	perennial	herb	1	0	
Senecio coronatus (Thunb.) Harv.	indigenous	perennial	herb	1	0	
Senegalia hereroensis (Engl.) Kyal. & Boatwr.	indigenous	perennial	tree	1	0	
*Sisymbrium orientale L.**	exotic	annual	herb	0	1	
*Solanum mauritianum Scop.**	exotic	perennial	shrub	0	1	
Solanum supinum Dunal var. supinum	indigenous	perennial	shrub	2	0	
*Sonchus asper (L.) Hill subsp. asper**	exotic	annual	herb	0	1	
Striga bilabiata (Thunb.) Kuntze subsp. bilabiata	indigenous	annual	herb	1	0	
Talinum arnotii Hook.f.	indigenous	annual	shrub	5	0	
Tarchonanthus camphoratus L. (S)	indigenous	perennial	shrub	1	0	
*Verbascum virgatum Stokes**	exotic	perennial	herb	0	1	
Viscum rotundifolium L.f.	indigenous	perennial	shrub	2	0	
Xenostegia tridentata (L.) D.F.Austin & Staples subsp. angustifolia (Jacq.) Lejoly & Lisowski	*indigenous*	perennial	herb	2	0	
Zornia capensis Pers. subsp. capensis	indigenous	perennial	herb	4	0	

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Supplementary Table S5: The 61 species recorded in 2012 not present in 1995 resampled sites survey and the number of sites in which they occurred. The grey highlight indicates a new species not in the 1995 resampled list for vacant lots/natural areas. However, 34 was recorded in other communities in Potchefstroom, 9 listed in other literature about Potchefstroom area around that time and 10 are listed in plant distribution book of the northern provinces of South Africa (Retief and Herman 1997). Only 9 of the species are 'new' in the area, 7 exotic garden escapes and 2 indigenous species from elsewhere in South Africa. Plant names according to Germishuizen et al. (2006). Number in natural area sites (NS), number in vacant lot sites (VLS).

All species	Origin	Lifespan	Life form	NS	VLS	Reference and occurrence
*Alcea rosea L.**	exotic	perennial	herb	0	1	Garden escapee
*Ammi majus L. var. glaucifolium (L.) Godr.**	exotic	annual	herb	0	1	Escape from cultivation (Retief and Herman 1997)
Anisodontea capensis (L.) Bates	indigenous	perennial	shrub	0	5	Indigenous garden escapee
*Anredera cordifolia (Ten.) Steenis**	exotic	perennial	herb	0	1	Garden escapee, invasive weed
Aristida stipitata Hack.	indigenous	perennial	grass	1	0	Road verges (Cilliers and Bredenkamp 2000)
*Arundo donax L.**	exotic	perennial	grass	0	1	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), wetlands (Cilliers et al. 1998), ruderal semi-natural communities (Cilliers 1998)
*Bidens pilosa L.**	exotic	annual	herb	4	0	Wetlands (Cilliers et al. 1998), railway reserves (Cilliers and Bredenkamp 1998), road verges (Cilliers and Bredenkamp 2000)
Bonatea speciosa (L.f.) Willd.	indigenous	perennial	herb	2	0	Railway reserves (Cilliers and Bredenkamp 1998)
*Bromus catharticus Vahl**	exotic	annual	grass	0	1	Intensively managed sites (Cilliers and Bredenkamp 1999a)
*Celtis sinensis Pers.**	exotic	perennial	tree	0	1	Natural areas 1995 non resampled sites (Cilliers 1998), wetlands (Cilliers et al. 1998), railway reserves (Cilliers and Bredenkamp 1998).
*Cestrum aurantiacum Lindl.**	exotic	perennial	shrub	0	3	Vacant lots 1995 non resampled sites (Cilliers 1998)
*Cirsium vulgare (Savi) Ten.**	exotic	annual	herb	2	0	Natural areas 1995 non resampled sites (Cilliers 1998), wetlands (Cilliers et al. 1998), railway reserves (Cilliers and Bredenkamp 1998).
*Citrus limon (L.) Burm.f.**	exotic	perennial	shrub	0	1	Garden escapee
*Convolvulus arvensis L.**	exotic	perennial	herb	1	1	Weed in cultivated soils (Retief and Herman 1997)
*Coreopsis lanceolata L.**	exotic	perennial	herb	0	2	Escape from cultivation (Retief and Herman 1997)
Cryptolepis oblongifolia (Meisn.) Schltr	indigenous	perennial	shrub	1	0	(Retief and Herman 1997)
*Cymbopogon caesius (Hook. & Arn.) Stapf **	indigenous	perennial	grass	11	0	Natural areas 1995 non resampled sites (Cilliers 1998)

Cynodon hirsutus Stent	indigenous	perennial	grass	0	1	Intensively managed sites (Cilliers and Bredenkamp 1999a)
*Datura ferox L.**	exotic	annual	herb	0	1	Ruderal semi-natural communities (Cilliers 1998)
*Datura stramonium L.**	exotic	annual	herb	0	2	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), Ruderal semi-natural communities (Cilliers 1998), railway reserves (Cilliers and Bredenkamp 1998), wetlands (Cilliers et al. 1998), road verges (Cilliers and Bredenkamp 2000)
Dicerocaryum eriocarpum (Decne.) Abels	indigenous	perennial	herb	1	0	(Bezuidenhout 1993)
*Dichondra micrantha Urb.**	exotic	perennial	herb	2	9	Natural areas 1995 non resampled sites (Cilliers 1998)
Eucalyptus camaldulensis Dehnh. (S)*	exotic	perennial	shrub	1	0	Ruderal semi-natural communities (Cilliers 1998)
*Euphorbia heterophylla L.**	exotic	annual	herb	0	1	Wetlands (Cilliers et al. 1998), intensively managed sites (Cilliers and Bredenkamp 1999a)
*Euphorbia prostrata Aiton**	exotic	annual	herb	0	2	Road verges (Cilliers and Bredenkamp 2000)
*Foeniculum vulgare Mill. var. vulgare**	exotic	perennial	herb	0	2	Disturbed places (Retief and Herman 1997)
Gynmosporia tenuispina (Sond.) Szyszyl.	indigenous	perennial	shrub	1	0	(Bezuidenhout and Bredenkamp 1988; Bezuidenhout et al. 1994)
Haplocarpha lyrata Harv.	indigenous	perennial	herb	1	0	Wetlands (Cilliers et al. 1998)
Helichrysum rugulosum Less.	indigenous	perennial	herb	5	1	(Bezuidenhout and Bredenkamp 1991; Bezuidenhout et al. 1994; Bredenkamp et al. 1994)
Hibiscus engleri K.Schum.	indigenous	perennial	herb	2	0	Natural areas 1995 non resampled sites (Cilliers 1998)
Indigofera vicioides Jaub. & Spach var. vicioides	indigenous	perennial	herb	1	0	Road verges (Cilliers and Bredenkamp 2000)
Ipomoea ommaneyi Rendle	indigenous	perennial	herb	1	0	Road verges (Cilliers and Bredenkamp 2000)
Kohautia amatymbica Eckl. & Zeyh.	indigenous	annual	herb	1	0	Road verges (Cilliers and Bredenkamp 2000)
Lotononis calycina (E.Mey.) Benth.	indigenous	perennial	herb	1	0	(Bredenkamp et al. 1994)
Loudetia simplex (Nees) C.E.Hubb.	indigenous	perennial	grass	1	0	Natural areas 1995 non resampled sites (Cilliers 1998)
Macledium zeyheri (Sond.) S.Ortíz subsp. Zeyheri	indigenous	perennial	herb	3	0	Natural areas 1995 non resampled sites (Cilliers 1998)
*Malva parviflora L. var. parviflora**	exotic	annual	herb	0	1	Ruderal semi-natural communities (Cilliers 1998)

*Melilotus alba Desr.**	exotic	annual	herb	2	3	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), ruderal semi-natural communities (Cilliers 1998), railway reserves (Cilliers and Bredenkamp 1998), wetlands (Cilliers et al. 1998), road verges (Cilliers and Bredenkamp 2000)
*Mirabilis jalapa L.**	exotic	perennial	herb	0	3	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), natural areas 1995 non resampled sites (Cilliers 1998), railway reserves (Cilliers and Bredenkamp 1998)
Moraea thomsonii Baker	indigenous	perennial	herb	0	1	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), railway reserves (Cilliers and Bredenkamp 1998), intensively managed sites (Cilliers and Bredenkamp 1999a)
*Morus alba L. var. alba**	exotic	perennial	tree	0	1	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), wetlands (Cilliers et al. 1998)
Neorautanenia ficifolius (Benth.) C.A.Sm.	indigenous	perennial	herb	1	0	Natural areas 1995 non resampled sites (Cilliers 1998)
*Nothoscordum gracile (Aiton) Stearn**	exotic	perennial	herb	0	1	Disturbed places (Retief and Herman 1997)
Ornithogalum viride (L.) J.C.Manning & Goldblatt	indigenous	perennial	herb	0	4	(Bezuidenhout 1993)
Oxalis obliquifolia Steud. ex Rich.	indigenous	perennial	herb	0	1	(Retief and Herman 1997)
Paspalum distichum L.	indigenous	perennial	grass	0	1	Wetlands (Cilliers et al. 1998)
Phyllanthus parvulus Sond.	indigenous	perennial	herb	2	0	(Bezuidenhout and Bredenkamp 1988; Bezuidenhout et al. 1994)
*Picris echioides L.**	exotic	annual	herb	0	1	Vacant lots 1995 non resampled sites (Cilliers and Bredenkamp 1999b), ruderal semi-natural communities (Cilliers 1998), wetlands (Cilliers et al. 1998), road verges (Cilliers and Bredenkamp 2000)
*Prunus armeniaca L.**	exotic	perennial	tree	1	0	Garden escapee
*Salvia splendens Sellow ex Roem. & Schult.**	exotic	perennial	shrub	0	1	Garden escapee
*Saponaria officinalis L.**	exotic	perennial	herb	0	1	Garden escapee
*Senna didymobotrya (Fresen.) Irwin & Barneby**	exotic	perennial	shrub	0	1	Woodland, disturbed places (Retief and Herman 1997)
Setaria lindenbergiana (Nees) Stapf	indigenous	perennial	grass	2	0	(Bredenkamp et al. 1994)

Setaria pumila (Poir.) Roem. & Schult.	indigenous	annual	grass	1	1	Ruderal semi-natural communities (Cilliers 1998), wetlands (Cilliers et al. 1998), road verges (Cilliers and Bredenkamp 2000)
Sida alba L.	indigenous	annual	shrub	0	1	(Retief and Herman 1997)
*Sorghum halepense (L.) Pers.**	exotic	perennial	grass	0	1	Ruderal semi-natural communities (Cilliers 1998), railway reserves (Cilliers and Bredenkamp 1998)
Sutera caerulea (L.f.) Hiern	indigenous	annual	herb	1	0	
Talinum caffrum (Thunb.) Eckl. & Zeyh.	indigenous	annual	herb	1	5	(Bezuidenhout et al. 1994; Bredenkamp et al. 1994)
Tragia rupestris Sond.	indigenous	perennial	herb	7	0	(Retief and Herman 1997)
Tristachya leucothrix Nees	indigenous	perennial	grass	1	0	(Bezuidenhout and Bredenkamp 1990; Bezuidenhout et al. 1994)
*Verbena officinalis L.**	exotic	annual	herb	0	7	Ruderal semi-natural communities (Cilliers 1998), railway reserves (Cilliers and Bredenkamp 1998)

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Local-scale sustainability? Insights from the interface between urban ecological research, socio-economic gradients, public opinion, municipal governance and future planning in Potchefstroom, South Africa.

Marié du Toit, Sarel Cilliers

Abstract

Globally, local governments are considered as the key role players in the success of sustainable strategies. As the premier discipline on urban environmental interactions, urban ecological research in cities worldwide can provide baseline data to inform effective planning strategies. In South Africa, descriptive urban ecological research started in the 1960s and largely focussed on only a few cities. Nonetheless, synthesis of the available research is rarely undertaken. In Potchefstroom extensive urban ecological research have been carried out. The aim of this study is to synthesize the urban ecological research carried out in Potchefstroom to determine its value as potential ecological baseline data. This can contribute to the advancement of urban ecological generalizations globally and simultaneously identify necessary gaps in the local information. South African urban morphologies display unique spatial patterns due to past discriminatory urban laws. This resulted in steep socio-economic gradients, and a further goal of this paper was to determine if these effects are visible in the observed vegetation patterns as well. This was clearly illustrated in the current study. The accrued biodiversity information was evaluated against municipal governance and future planning strategies to elucidate current sustainable trajectories. Despite clear sustainability goals in municipal management plans, implementation thereof is largely lacking. Moreover, none of the urban biodiversity studies carried out were incorporated into the municipal integrated development plan. Better synergy is needed between scientists, citizens and decision-makers to ensure advancement towards sustainable solutions.

Keywords: Urban ecology, urban biodiversity, green infrastructure, municipal governance, sustainable planning.

Introduction

Cities as the major habitation of more than half of the world's population (United Nations, 2014) are central in determining the outcomes of sustainable solutions for socio-ecologically resilient liveable futures. Moreover, "*the future of humanity lies in cities*" (Annan, 2002). The discipline of urban ecology has positioned itself as a major scientific discipline that can play a key role in assisting urban areas towards more sustainable trajectories (Wu, 2014). However, lack of baseline ecological data seriously impairs strategic planning and conservation efforts in many urban areas (Cilliers, Müller, & Drewes, 2004). Conservation is a central tenant of sustainable paradigms (Hutton & Leader-Williams, 2003; Knapp, 2003; Orr, 2002). However, Knapp (2003) argues for critical rethinking in our concept of conservation and the implicit acknowledgement of its dynamic nature. In this regard, science—its unremitting advance and fund of acquired knowledge—is essential for the effective conservation of the resilience and interconnectivity of the environment (Knapp, 2003). However, in Africa conservation is a highly contentious issue (Githiru, 2007; Wilhelm-Rechmann & Cowling, 2011, see also discussion in paper 1 of this thesis). Conservation is not equally valued, and Githiru (2007) envisions this as a stakeholder divide, where some, such as environmental NGOs and various individuals, contend with those pursuing other priorities unconvinced of its importance—views held by most governments and the general public. For sustainable development efforts to succeed public support and participation is essential (Macnaghten & Jacobs, 1997). Social assessments should be included in conservation projects (Cowling & Wilhelm-Rechmann, 2007), together with environmental education (Le Maitre et al., 1997) and effective communication (Githiru, 2007).

South African legislation mandates local governments through the Local Government: Municipal Systems Act 32 of 2000 (South Africa, 2000) and the Spatial Planning and Land Use Management Act 16 of 2013 (South Africa, 2013) to have compulsory five-year municipal integrated development plans (IDP) wherein there must be a spatial development framework (SDF). The Spatial Planning and Land Use Management Act (SPLUMA) decrees that the SDF should "include a strategic assessment of the environmental pressures and opportunities...including the spatial location of environmental sensitivities" (South Africa, 2013). Furthermore, a specific objective listed in the SPLUMA is sustainable and efficient land use (South Africa, 2013). Transdisciplinary interactions between urban ecologists, spatial planners, environmental managers, municipal decision-makers and the general public should be actively encouraged to advance towards sustainable urban solutions (Cilliers, du Toit, Cilliers, Drewes, & Retief, 2014). However, many smaller municipalities lack adequate ecological baseline data (Cilliers, 2010). Moreover, poor implementation and a lack of capacity are often stated as problems occurring in municipalities (Carden & Armitage, 2013; Wilhelm-Rechmann & Cowling, 2013). The lack of detailed ecological data for South African urban areas was addressed by wide-ranging studies of urban open spaces in some cities of the North-West Province (e.g. Cilliers, Schoeman, & Bredenkamp, 1998; Cilliers & Bredenkamp, 2000; Jonas, 2007; Smith, 2004; van Wyk, Cilliers, & Bredenkamp, 1997). Urban ecological research was particularly intensive in Potchefstroom. However, no comprehensive consolidation of the existing urban ecological research has yet been undertaken.

The aim of this study is to synthesize the urban ecological research carried out in Potchefstroom to determine its value as potential ecological baseline data. Specifically, (1) to combine all the urban biodiversity studies carried out and to compare them with global literature, (2) to identify the gaps in the existing research, and (3) to determine if the steep socio-economic gradient found in Potchefstroom correlate to observed species patterns. This is evaluated against the current municipal IDP and SDF, municipal management strategies, and public opinion to inform progress towards sustainable future scenarios.

Methods

Study area

The study area includes the city of Potchefstroom (26˚ 42′ 53′′ S; 27˚ 05′ 49′′ E) and its immediate natural surroundings, situated in the North-West Province of South Africa at the southernmost tip of Africa (Fig. 1). The city covers a 55 km^2 area with a population of approximately 170 868 in 2013 (Maxim Planning Solutions, 2014). The mean annual rainfall is 600 mm received predominantly in summer months (October to March), with average temperatures ranging between 30°C and 0°C and frequent frost in winter. The central part of the city is laid out along the western banks of the Mooi River on a flat plain, the western side of the city consisting of the residential areas of Ikageng, the Ikageng extension, Mohadin, and Promosa are situated amongst a series of small hills and ridges (Fig. 1). Potchefstroom is situated in the Grassland biome at the confluence of three vegetation types, namely the Rand Highveld Grassland, Carletonville Dolomite

Grassland and the Andesite Mountain Bushveld (Mucina & Rutherford, 2006). The latter being Savanna elements as found on the hills, rocky outcrops and ridges in the area.
Potchefstroom history and socio-economic context

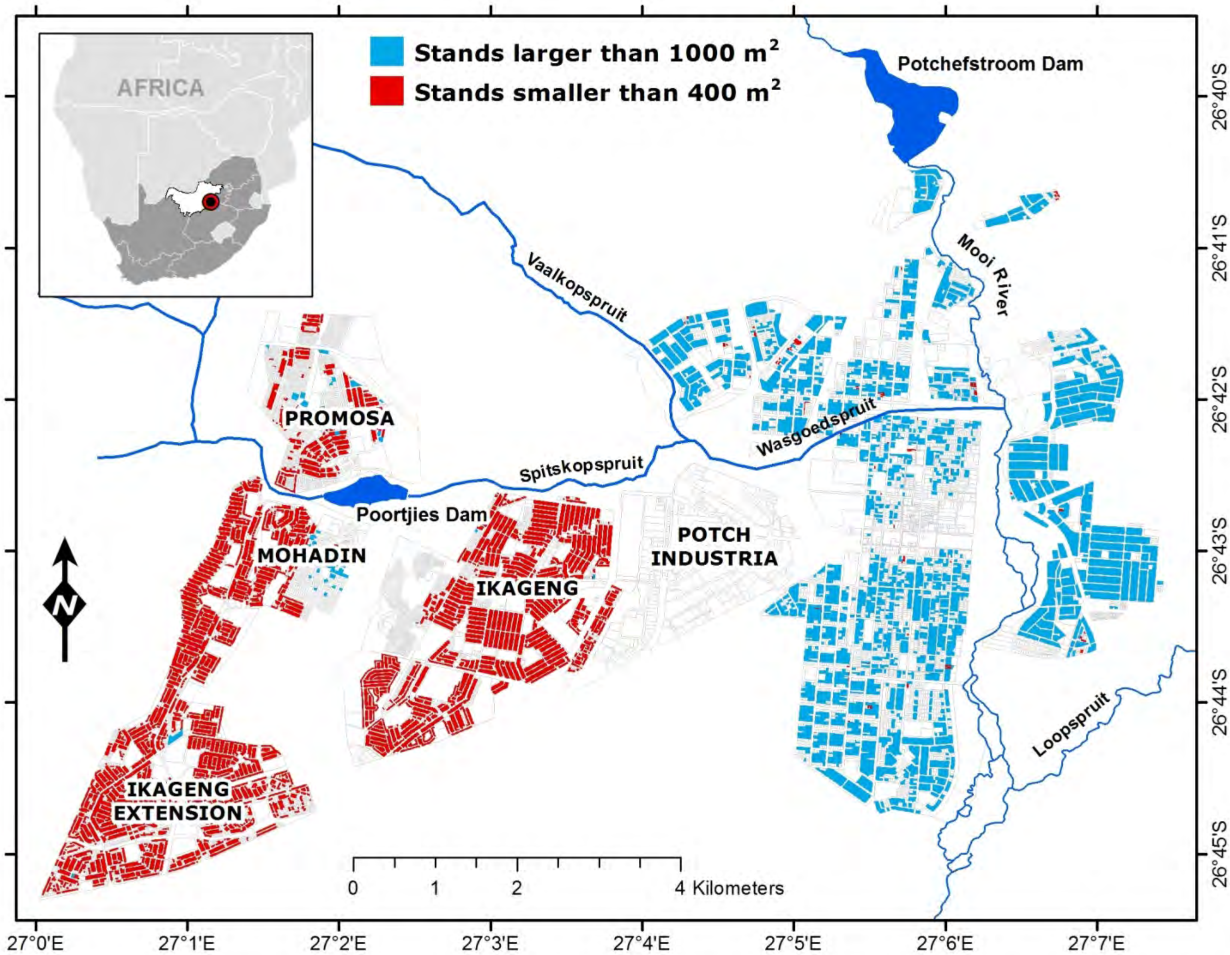

Fig. 1. Layout of Potchefstroom indicating the differences in stand sizes between the township areas and the previously white residential areas along the Mooi River. The inset map shows the location of Potchefstroom in the North-West Province of South Africa at the southernmost tip of Africa.

Potchefstroom was established in 1838 as a temporary settlement of Dutch farmers and settlers during the Great Trek out of the British-ruled Cape Colony (Badenhorst, 1939). Socio-economically, the current spatial organization of residential areas is distinctive. Segregation of residents based on their specific ethnic groups began in 1877 with the proposal of a separate residential area (called "location") for natives (Coloured and African people) (Neser, 1967). The first "location" was situated at the southern end of the town, with an additional specific demarcated area for people of Indian origin as well. Further segregation took place during the 1950s. The Group Areas Act of 1950 provided for the compulsory zoning of all urban areas into exclusive group areas (Christopher, 2001). All residents in the old "location" were to be resettled in newly proclaimed separate townships in the town commonage area along the western border of the urban area. Resettlement of the residents of the township areas started in 1957 with Ikageng, then Promosa in 1969 and lastly, Mohadin in 1971 (Hellberg, 1970; Neser, 1967) (Fig. 1). The advent of democracy in 1994 and the lifting of urban restriction laws saw the rapid influx of thousands of South Africans to cities and towns. In Potchefstroom, this resulted in the expansion of the township areas and the development and growth of the Ikageng Extension area (Fig. 1). However, 20 years after 1994, the residential areas still remain largely segregated.

A steep socio-economic gradient is present from the poorer western side to the affluent eastern side of the city (Fig. 2). In the study of Lubbe, Siebert, and Cilliers (2010) on domestic gardens in Potchefstroom, they determined the socio-economic status (SES) of 100 garden owners along a transect through Potchefstroom. Five parameters were chosen, obtained from government census data, to calculate the SES namely unemployment, household size, number of rooms, access to basic services, and schooling status (Table 1). A clear gradient was observed from lower SES (1,2,3) in the west to higher SES (4,5) in the east (Fig. 2). This gradient is also evident from the large disparity between the average stand sizes of the townships (non-white residential areas) of Mohadin, Ikageng, Promosa and the traditional white residential areas in the eastern part of Potchefstroom (Fig. 1).

Table 1

The parameters used to describe the five socio-economic classes quantified in Potchefstroom as determined by Lubbe et al. (2010).

SES (class)	Unemployment[1]	Household size[2]	Number of rooms[3]	Access to basic services[4]	Schooling status[5]
1	46±5	28±8	44±18	7±9	14±4
2	33±2	27±9	40±10	11±17	24±10
3	25±3	38±5	27±14	5±9	9±5
4	15±2	23±17	23±12	2±1	10±8
5	4±1	13±1	10±1	1±0	2±0

[1] % unemployed household members, [2] % households with five or more persons, [3] % households with one or two rooms only, [4] % households with pipe water >200 m away, [5] % individuals with no schooling per household.

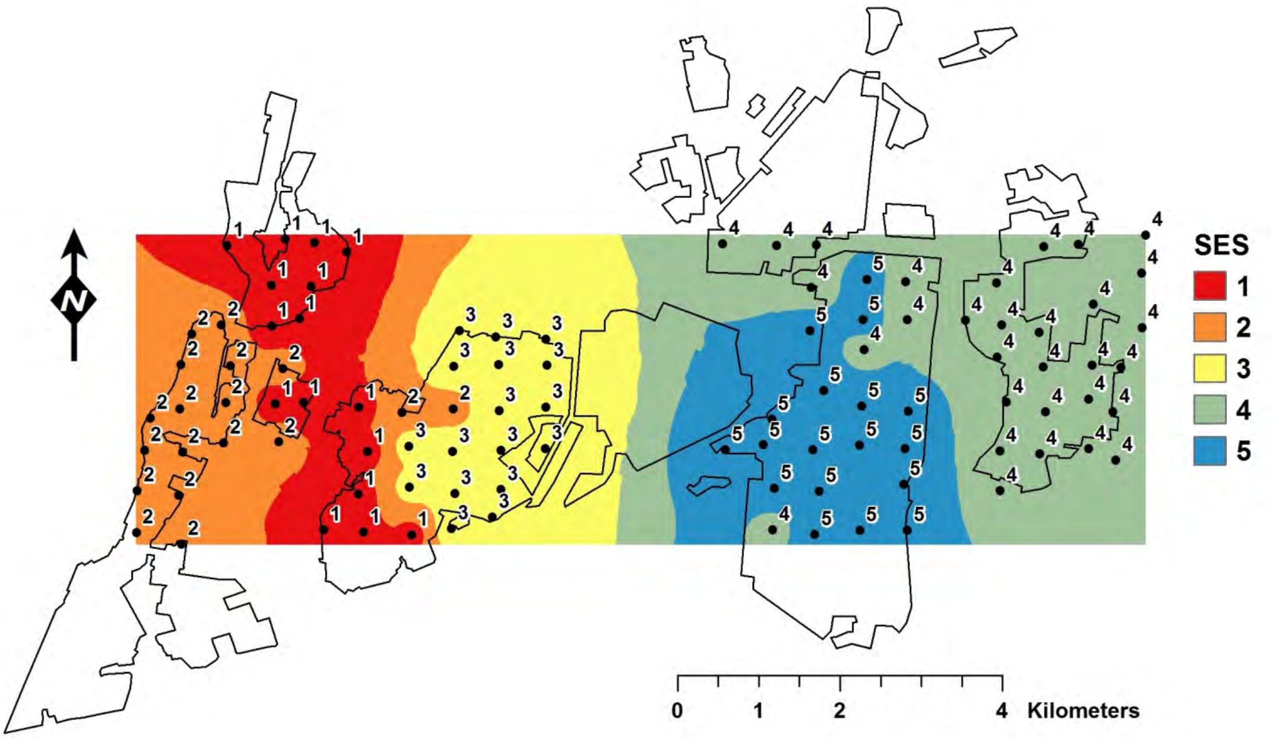

Fig. 2. Map of the steep socio-economic gradient present in Potchefstroom based on the calculation of socio-economic status classes from the study of Lubbe et al. (2010). Class one represents the poorest residents whereas class five represents the wealthiest (Table 1).

In a South African context, Potchefstroom has a long history of urban ecology, the first study describing the influence of urbanization on biodiversity in the Potchefstroom urban region was that of Louw (1951). He did not describe the vegetation inside the city borders, but included the town commonage area in his description of the vegetation in the greater Potchefstroom region. Listed in Table 2 is a chronological timeline of the major urban developments in Potchefstroom and all the available urban ecological research to date.

Urban biodiversity

We summarized the findings of 13 biodiversity studies carried out since 2000 and compared them to existing literature to determine how the patterns observed in Potchefstroom correlated with findings elsewhere. In South Africa, the Local Government: Municipal Systems Act 32 of 2000 mandates compulsory municipal integrated development plans (IDP) wherein must be contained the Spatial Development Framework (SDF). Based on the findings of the urban biodiversity and socio-economic gradient results, we evaluated how this is reflected in the current municipal IDP and specifically the SDF which indicates future development trajectories.

Data analysis

Kriging interpolation maps were created in ArcMap 10 (ESRI, 2010) of all the biodiversity studies that had sufficient coverage across Potchefstroom. These maps were used to determine if socio-economic gradients influenced observed biodiversity patterns. The total species richness and percentage indigenous species richness were interpolated to create the maps.

Table 2

Chronological timeline of Potchefstroom listing noteworthy historical events and the available research carried out in the field of urban ecology to date.

1838	Potchefstroom founded (10 km upstream from current location)
1841	Town relocated to current location (van den Bergh, 1992)
1880-1881	First Anglo Boer War
1899-1902	Second Anglo Boer War
1903	Potchefstroom acquired municipal status
1951	Ecological study of the vegetation of the Potchefstroom region (Louw, 1951)
1954	Development of Ikageng started (Neser, 1967)
1956	Potchindustria laid out
1959	Promosa laid out (Neser, 1967)
1960	Study on the birds of Potchefstroom and the surrounding district (Brandt, 1960)
1967	Revised Potchefstroom bird list (Brandt, 1967).
1971	Mohadin suburb laid out (Hellberg, 1970)
1994	First democratic elections in South Africa, advent of rapid urbanization rates.
1995-1996	Phytosociological study of the urban open spaces (Cilliers et al., 1998; Cilliers, 1998; Cilliers & Bredenkamp, 1998, 1999a, 1999b, 2000; Cilliers, Van Wyk, & Bredenkamp, 1999)
1999-2001	Vegetation dynamics of urban open spaces subjected to different anthropogenic influences (Putter, 2004)
2001	Application of the eco-circle method of urban vegetable cultivation (Cilliers, 2010; Cilliers, Matjila, & Sandham, 2007)
2002	Urban biotope mapping (Cilliers et al., 2004; Drewes & Cilliers, 2004; Rost, 2002; Röthig, 2002)
2002-2003	Assessment of epigeal arthropods along an urbanization gradient (Jonas, 2007)
2003	Birds and the urban ecology of Potchefstroom (Smith, 2004)
2005	Adaptation of trees to the urban environment: *Acacia karroo* in Potchefstroom (Pelser, 2006)
2005	Social aspects of eco-circles in Ikageng (Cilliers et al., 2007)
2005	EIA specialist report of the Mooi river (Bouwman, 2005)
2005-2006	Investigation of faecal pollution and occurrence of antibiotic resistant bacteria as a function of a changed environment (Pantshwa, 2006)
2006	Fragmentation and plant invasions in indigenous grasslands along an urban-rural gradient (Cilliers, Williams, & Barnard, 2008)
2006	The implementation of urban greening projects for energy efficiency and greenhouse gas reductions (Nel, 2006)
2006-2007	Riparian bird diversity (Wyma, 2012)
2007	An ecological study of the plant communities and degraded areas of the Highveld National Park (Daemane, Cilliers, & Bezuidenhout, 2010, 2012)
2007-2008	Investigation of the microbial diversity and functionality of soil in fragmented SA grasslands along an urbanization gradient (Jansen van Rensburg, 2010)
2009	Comparison of the urban domestic garden flora along a socio-economic gradient in the Tlokwe City Municipality (Lubbe et al., 2010; Lubbe, Siebert, & Cilliers, 2011)
2009	The development and use of a land-use suitability model in spatial planning (Cilliers & Drewes, 2010)
2010	Plant and insect diversity of vegetable gardens along a socio-economic gradient (Botha, 2012)
2011	Publication on the North-West University botanical garden (Smit, Cilliers, Siebert, & Willis, 2011)
2012	Temporal vegetation dynamics and time lags in remnant natural grassland (Papers 2, 3 this thesis)
2012	Grassland diversity and landscape functionality along an urbanization gradient (van der Walt, 2013; van der Walt, Cilliers, Du Toit, & Kellner, 2015a; van der Walt, Cilliers, Kellner, Du Toit, & Tongway, 2015b)
2012-2013	Amphibian diversity along an urbanization gradient (Kruger, Hamer, & Du Preez, 2015)
2013	Ecosystem services, determining the economic value of urban green spaces (Cilliers, Cilliers, Lubbe, & Siebert, 2013).

Results

Biodiversity patterns

In total, the results of 13 studies carried out in Potchefstroom were summarized and compared to relevant global literature (Table 3). Four of the studies described multiple biotic groups (Botha, 2012; Bouwman, 2005; Jansen van Rensburg, 2010; Kruger et al., 2015). Of the 13 studies, ten focussed on vegetation describing biotopes, managed open spaces, riparian vegetation, an indigenous tree species *Acacia karroo*, garden flora including vegetable gardens and lawns, and remnant natural vegetation patches. A specialist study was carried out on the Mooi river along its course through the urban area, as part of an environmental impact assessment, representing ten biotic groups namely algae, diatoms (specific separate study from the general algae group), riparian vegetation, aquatic macroinvertebrates, butterflies, fish, amphibians, reptiles, birds, and mammals. The rest of the studies include two focussing on arthropods and single studies on birds, fish, amphibians, and bacterial and fungal micro-organisms.

Table 3
Summary of the findings of urban biodiversity studies in Potchefstroom conducted since 2000. The results are compared to other existing publications.

Reference	Focal species	SR	Results	Other literature
(Rost, 2002; Röthig, 2002)	Vegetation (Biotopes)	-	13 main biotope types, including their conservation status; ↓ of indigenous species with increased urbanization, patch size correlates to diversity ↑	Biotope mapping successfully carried out around the globe (Hong, Song, Byun, Yoo, & Nakagoshi, 2005; Löfvenhaft, Björn, & Ihse, 2002; Sukopp & Weiler, 1988); indigenous flora ↓ from fringe to city core (Kowarik, 1990; Williams, Morgan, McDonnell, & McCarthy, 2005); diversity ↑ in larger urban patches (Bastin & Thomas, 1999)
(Putter, 2004)	Vegetation (managed open spaces in different biotope types)	-	Changes in management practices and trampling influenced species composition and abundance	Species composition influenced by management practices (e.g. mowing, burning, trampling, herbicide use) (Cilliers & Bredenkamp, 2000; Gibson, Seastedt, & Briggs, 1993),
(Smith, 2004)	Birds	72	Bird species ↑ abundance in the agricultural areas, the eastern residential areas and the military areas; highest species richness occurred in less highly urbanised areas, and was lowest in the more highly urbanized areas (industrial)	Distribution patterns in natural bird communities differ from those found in urban communities (Jokimäki et al., 2011); urbanization↓ in indigenous species and ↑ in exploiters (Cam, Nichols, Sauer, Hines, & Flather, 2000; Chace & Walsh, 2006; Kark, Iwaniuk, Schalimtzek, & Banker, 2007)
(Bouwman, 2005)	Algae (riparian biodiversity)	34	Rich algal community, algal composition indicate low levels of eutrophication, organic substance pollution, high concentration total dissolved-salts.	Urban streams often polluted with organic contaminants (Paul & Meyer, 2001). Urbanization influences algal composition (Taylor, Roberts, Walsh, & Hatt, 2004)
	Diatoms (algae) (riparian biodiversity)	87	No rare or endemic species. Biological Diatom Index (Lenoir & Coste, 1996) scores indicated that the river is of good quality with some locations of moderate quality, due to pollution sources along the river.	Urban streams are degraded, many pollutants can be present (Paul & Meyer, 2001; Walsh et al., 2005). Diatoms good indicators of water quality, urban and rural assemblages differ (Duong, Feurtet-Mazel, Coste, Dang, & Boudou, 2007; Walker & Pan, 2006).

	Vegetation (riparian biodiversity)	209	No rare or endangered species. Community composition reflects anthropogenic activities, three areas degraded due to overgrazing. Naturalized exotic tree, dominant along river banks. ↑ number of declared weeds and invaders and exotics. Riparian Vegetation Index (Kemper, 2001) also indicated the degraded state.	↑ exotic species in degraded, anthropogenically altered rivers (Maskell, Bullock, Smart, Thompson, & Hulme, 2006). In Australia, many watercourses dominated by naturalized and invasive willow trees (Zukowski & Gawne, 2006).
	Aquatic macro-invertebrates (riparian biodiversity)	28	The SASS 5 bio-indicator system (Chutter, 1998) indicated that the river system was in a moderately degraded state, fairly low number of taxa.	Many urban streams degraded with lower biotic richness (Walsh et al., 2005). Urbanization degrades macroinvertebrate communities (Walsh, Sharpe, Breen, & Sonneman, 2001). Macro-invertebrates good indicators of anthropogenic impacts (Carter, Purcell, Fend, & Resh, 2009).
	Butterflies (riparian biodiversity)	32	Extensive exotic trees along Mooi river severely degraded original communities. River contains suitable habitat for a endangered species and was observed.	Lower species richness of butterflies in urban riparian areas, but some rare species can still persist (Blair, 1999; Nelson & Nelson, 2001)
	Fish (riparian biodiversity)	11	Low endemic fish diversity, 5 introduced species. No endangered species, the most sensitive species is the Smallmouth Yellowfish, whose numbers are declining across SA.	Decline of fish SR in urban streams, (Paul & Meyer, 2001), especially sensitive species (Walsh et al., 2005). Introduced species common feature in urban streams (Paul & Meyer, 2001).
	Amphibians (riparian biodiversity)	7	One endangered species, the Giant Bullfrog.	Urbanization negatively influence amphibians (Hamer & McDonnell, 2008) Endangered species can persist in urban areas, but very sensitive to specific habitat requirements (Francesco Ficetola & De Bernardi, 2004)
	Reptiles (riparian biodiversity)	14	No endangered species.	Lower species richness along riparian corridors in urban areas (Burbrink, Phillips, & Heske, 1998), big enough terrestrial habitat around wetlands essential for sustaining biodiversity (Semlitsch & Bodie, 2003)
	Birds (riparian biodiversity)	74	Large bird diversity, however exotic species such as the Common Indian Myna is also abundant. Biodiversity ↑ at southern end of the city.	Urbanization↓ in indigenous species and ↑ in exploiters (Cam et al., 2000; Chace & Walsh, 2006; Kark et al., 2007). Urbanization affects riparian bird communities, species richness ↓, a common exotic species abundant (Miller, Wiens, Hobbs, & Theobald, 2003)
	Small mammals Larger mammals (riparian biodiversity)	7 6	Rare species found, but no endangered species.	Urban populations limited by predation and fragmentation (Baker, Ansell, Dodds, Webber, & Harris, 2003)
(Pelser, 2006)	Vegetation (*Acacia karroo*) Tree vitality.		Tree vitality ↓ from rural to urban, despite this, tree appraisal method indicate some urban trees still with high monetary values.	Similar to method used by Hermans et al. (2003) and corroborate their prediction that forest trees ↑ vitality than urban trees. Urban trees have high monetary values (Nowak, Crane, & Dwyer, 2002)

(Jonas, 2007)	Epigeal arthropods	52	Seasonal changes large impacts on abundance and morphospecies numbers; ants individuals dominant, SR ↓ in urban sites; beetle morphospecies. ↑ in urban sites; spiders least affected however ↑ in urban sites	Ants dominant in urban surveys (Andersen, Fisher, Hoffmann, Read, & Richards, 2004); beetle diversity generally ↓in urban sites (Ishitani, Kotze, & Niemelä, 2003; Niemelä & Kotze, 2009; Sadler, Small, Fiszpan, Telfer, & Niemela, 2006), however some cities also show ↑ in urban sites (Niemelä & Kotze, 2009); spider overall abundance along urban-rural gradient no statistical difference (Alaruikka, Kotze, Matveinen, & Niemelä, 2002)
(Jansen van Rensburg, 2010)	Microorganisms (Bacteria and fungi)	14	↑ average aerobic heterotrophic bacterial levels in urban soil samples; fungal levels ↑ in soil from rural sample sites; ↑ dehydrogenase, β-glucosidase and urease activity in urban samples.	Heavy metals, base cation and acidic deposition could have an effect on the composition of microbial communities in soil (Cookson et al., 2007); Urban forest stands along an urban-rural gradient reduced fungal and microarthropod populations (Pouyat, Parmelee, & Carreiro, 1994)
	Vegetation (remnant natural grasslands)	108	Plant species composition different between rural, suburban and urban sites. Rural ↑ SR.	Urbanization influences plant communities, ↑ SR in rural surroundings than in urban core (McKinney, 2002)
(Lubbe, 2011; Lubbe et al., 2010, 2011)	Vegetation (garden flora)	835	145 plant families were recorded for the domestic gardens, 501 plant genera, 835 species; 484 naturalized and cultivated alien species, 88 declared invader and weed species; socio-economic status of the inhabitants affected the plant species distribution in the study area	Escaped garden ornamentals are a major source of alien invasive species (Dehnen-Schmutz, Touza, Perrings, & Williamson, 2007; Foxcroft, Richardson, & Wilson, 2008; Meyer & Lavergne, 2004). Most gardens contain ↑ plant species than any other land-use type in urban environments (Thompson et al., 2003)
(Botha, 2012)	Vegetation (vegetable gardens and lawns)	88	Lower income classes ↑ plant diversity, vegetable gardens ↑ (91% of species) than lawns. High number of exotic species in all classes.	Domestic gardens neglected in urban ecological research (Smith, Thompson, Hodgson, Warren, & Gaston, 2006), lawns most understudied (Thompson, Hodgson, Smith, Warren, & Gaston, 2004). Diversity ↑ along socio-economic gradient (Martin, Warren, & Kinzig, 2004).
	Arthropods	495	Higher income gardens significantly ↑ arthropod diversity values. Vegetable gardens ↑ than lawns.	Gardens much ↑ abundance compared to vacant lots or forests (Philpott et al., 2013). Lawns ↓ SR than structurally enhanced road islands (Whitmore, Crouch, & Slotow, 2002).
Paper 2, this thesis	Vegetation (Remnant natural grasslands, perennial species)	-	Woody vegetation indigenous species time lags of average 20 years, disturbance species average 40 year time lags, correspond to major urbanization growth patterns. Grasslands only time lags with disturbance species average 15 year lag.	No corresponding urban study carried out, however study of 22 urban areas indicate extinction debts (Hahs et al., 2009). Time lags in semi-natural grasslands 30 - 100 years (Helm, Hanski, & Partel, 2006; Koyanagi et al., 2012; Lindborg & Eriksson, 2004). No time lags found in Belgium grasslands (Adriaens, Honnay, & Hermy, 2006).

Paper 3, this thesis	Vegetation (temporal dynamics, remnant natural grasslands)	298	In vacant lots indigenous species richness(ISR) ↑*, exotic species richness (ESR) ↑*, and disturbance species richness (DSR) ↑. Grassland ISR ↓*, ESR ↓*, DSR ↓*. Woody ISR ↓*, ESR =, DSR ↓*.	Decline in indigenous SR also observed in other urban areas (Chocholoušková & Pyšek, 2003; Tait, Daniels, & Hill, 2005; Williams, Morgan, McCarthy, & McDonnell, 2006). Increase of exotic species inside urban areas (Roy, Hill, & Rothery, 1999), consistent with our vacant lot findings.
(van der Walt et al., 2015a; van der Walt et al., 2015b)	Vegetation (remnant natural grasslands in urban and exurban areas)	350	Urban ↓ mean SR, ↓* diversity, ↓ evenness than peri-urban/rural. Urban ↑* exotic SR. Fine-scale biophysical functional similarities due to management practices i.e. mowing in urban patches.	German urban areas ↑ SR than rural areas (Kühn, Brandl, & Klotz, 2004). No real differences in SR along gradient in remnant patches in Melbourne (Hahs & McDonnell, 2007)
(Kruger et al., 2015)	Amphibians (all water bodies)	7	Anurans present in 74% of water bodies, 2 species only found in surrounding rural areas, 1 species ubiquitous, ↑ SR on urban fringe, no species in or near CBD. ↑ SR in well-vegetated water bodies.	↓ SR in ↑ urban densities (Hamer & Parris, 2011; Pillsbury & Miller, 2008). ↑ SR in ponds with ↑ green open spaces, and species specific responses to urbanization (Hamer & Parris, 2011).
	Predatory fish (all water bodies)	4	Predatory fish in 64% of the water bodies. ↑ anuran SR had ↑ fish SR	Predatory fish impacts amphibian communities, negative relationship with anuran larval abundance (Hamer & Parris, 2013)

* statistically significant, SR = species richness, ↑ = high, ↓ = low.

Socio-economic impacts on biodiversity patterns

The studies used to test the effects of a socio-economic gradient on observed biodiversity patterns included the study of Smith (2004) on urban bird distributions (Fig. 3), the domestic garden study of Lubbe (2011) (Fig. 4), the sampling sites used to create the urban biotope map of Potchefstroom (Rost, 2002; Röthig, 2002) (Fig. 5), the results of the vegetation sampling carried out in paper 3 of this thesis (Fig. 6) and the study of Cilliers et al. (2013) on ecosystem services of urban green spaces (Fig. 7). All the maps show that the observed biodiversity patterns differ along the socio-economic gradient.

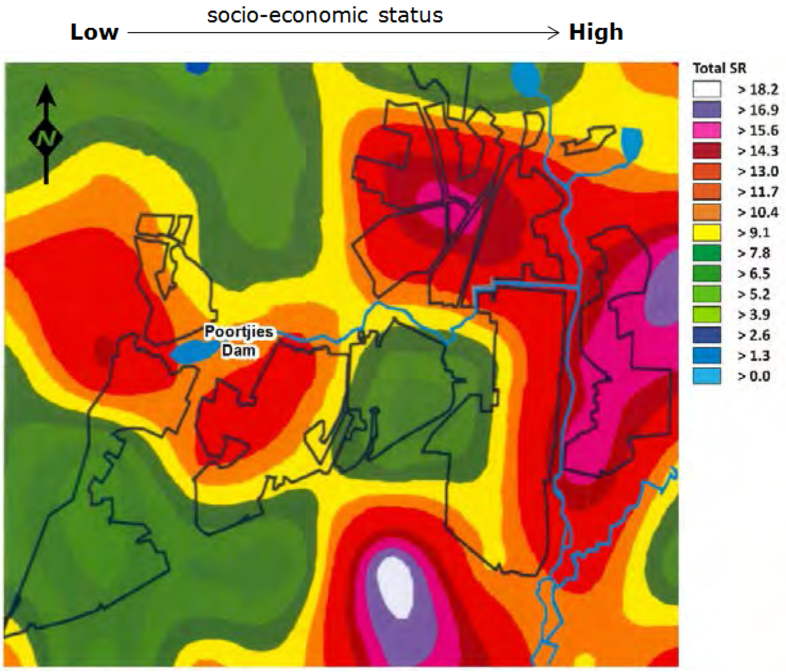

Fig. 3. Interpolation map of the total species richness of birds interpolated over Potchefstroom. Map adapted from Smith (2004).

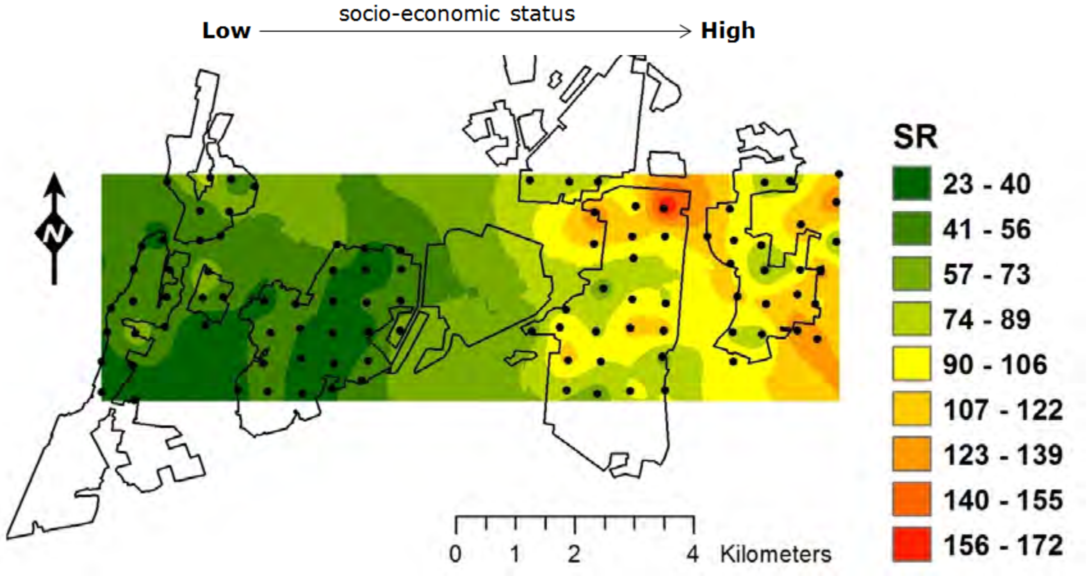

Fig. 4. Interpolation map of the total species richness recorded in domestic gardens along the socio-economic gradient (Lubbe, 2011).

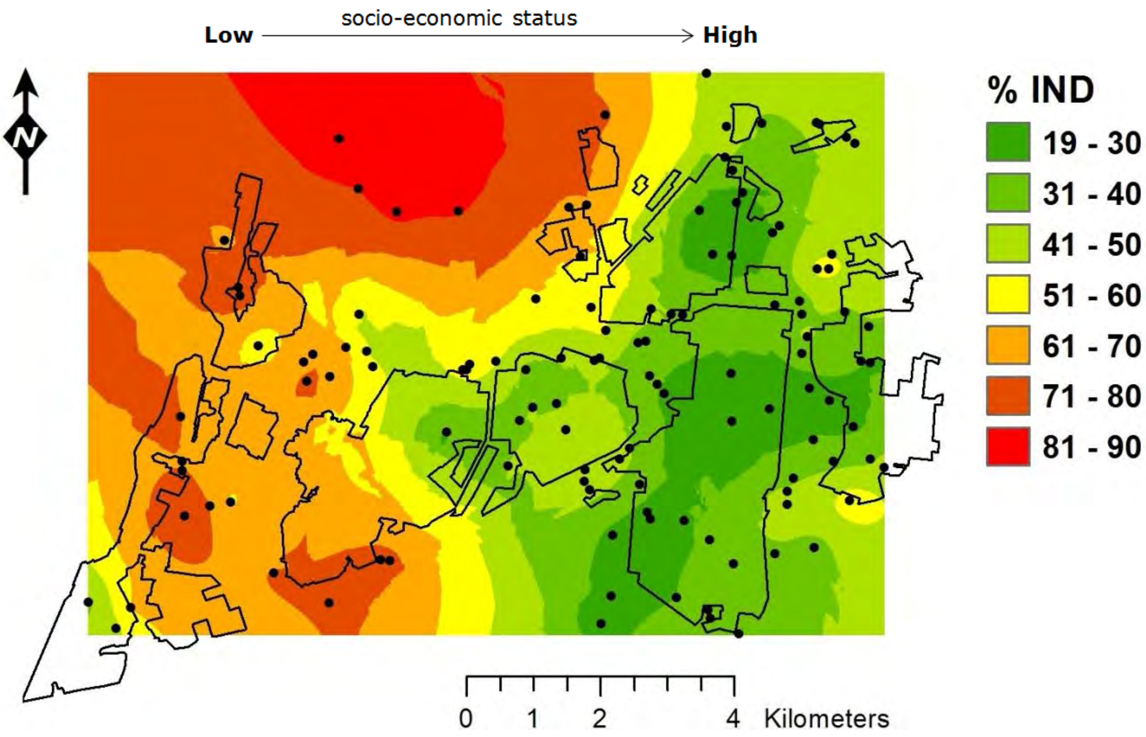

Fig. 5. Interpolation map of the percentage indigenous species of vegetation sampled as part of a biotope mapping study in Potchefstroom (Rost, 2002; Röthig, 2002)

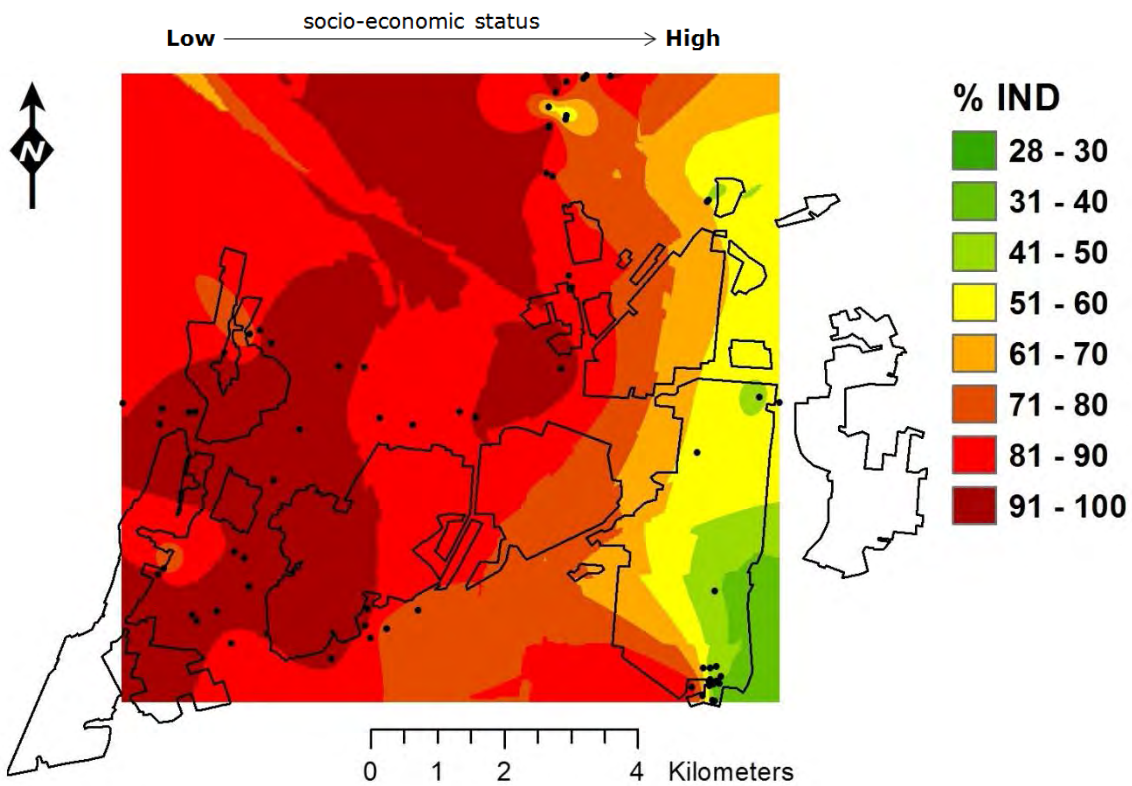

Fig. 6. Interpolation map of the percentage indigenous species of vegetation sampled in natural areas and vacant lots in 2012 (Paper 3 of this thesis).

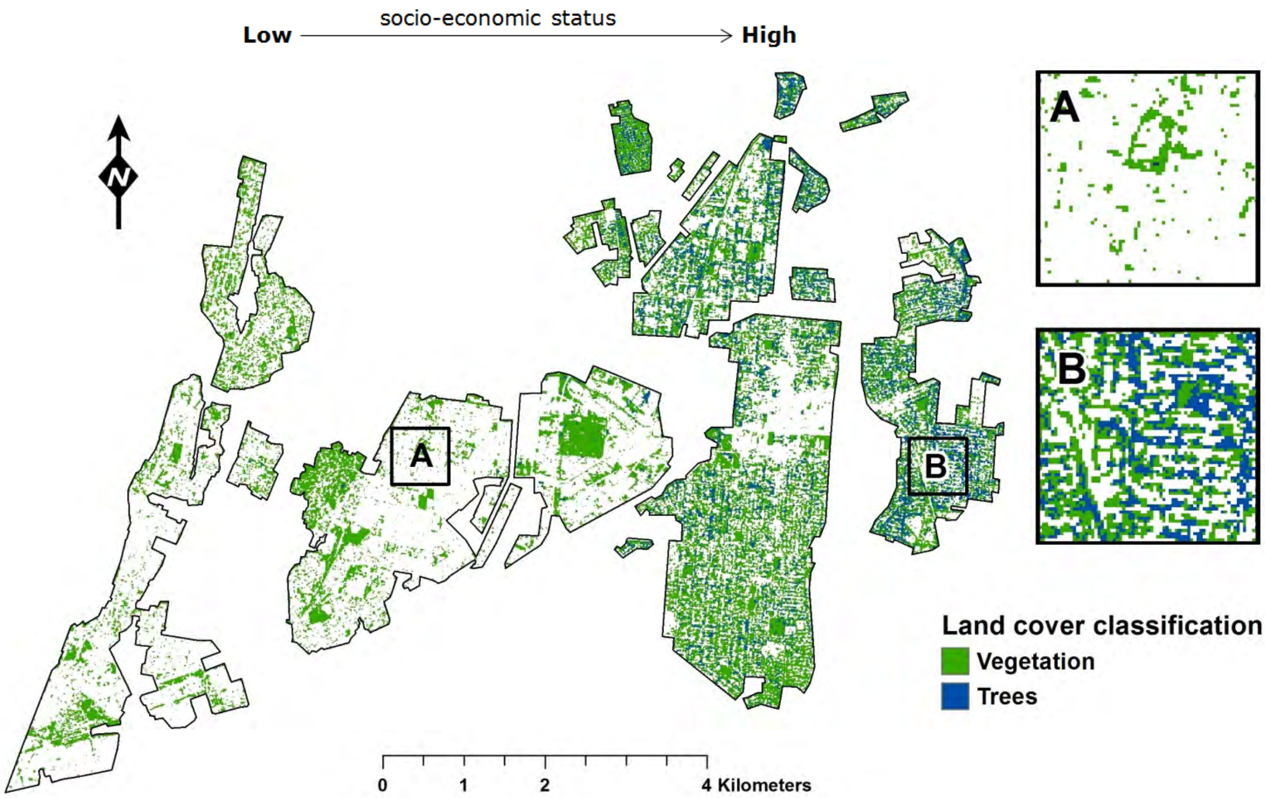

Fig. 7. Land cover classification map of Potchefstroom indicating pixels classified as vegetation and trees for all the built up areas (adapted from Cilliers et al., 2013). The zoomed in inset areas (A and B) clearly indicate the differences in vegetation cover along the socio-economic gradient.

Discussion

Biodiversity patterns

Potchefstroom has amassed an impressive array of urban biodiversity studies. By far the most studies focussed on vegetation (10), this trend was also found in the comprehensive literature review carried out on South Africa (Paper 1 of this thesis). The comparability of the results obtained in Potchefstroom with other global findings allow valuable additions to determining global urbanization generalizations, especially since Potchefstroom is much smaller (55 km^2, population 170 868) than many of the study areas it was compared to. Some of the studies included address global research gaps, such as the study carried out by Botha (2012) focussing on the comparative diversity of arthropods in vegetable gardens and lawns. Other studies focussed on individual aspects of the study, but no similar literature was found. Paper 2 of this thesis also has no current global comparison focussing on urban vegetation time lags. The study of van der Walt (2013) was the first to apply landscape functionality analysis in an urban area and proved that remnant urban grassland patches can be just as functional biophysically as natural grasslands in surrounding rural areas (van der Walt et al., 2015a; van der Walt et al., 2015b). The results of the study of lower species richness in urban areas is also contradictory to what is documented elsewhere (Hahs & McDonnell, 2007; Kühn et al., 2004). The study of Kruger et al. (2015) on amphibian communities was also a first in an African city. Moreover, their findings of high anuran larval species richness in spite of high predatory fish species richness is also contradictory to other studies documenting a negative relationship between those two factors (Hamer & Parris, 2013). However, most of the biodiversity groups were represented by only one study that greatly impairs generalizations on the observed patterns found in

Potchefstroom. Time frames, seasonality, and limited sampling sites all constrained research interpretations. In a South African context where very few municipalities have any ecological data, Potchefstroom stands out. However, the ecological utility of using these results to inform the sustainable discourse will remain limited if continuous monitoring and more studies on underrepresented biotic groups is not carried out.

Socio-economic impacts on biodiversity patterns

South African cities have unique spatial morphologies exhibiting stark socio-economic gradients (Davies, 1981); Potchefstroom is no exception (see Lubbe et al., 2010). These socio-economic gradients are clearly visible in the differences between stand sizes and socio-economic status in the previous township areas and the previously white residential areas (Figs. 1 and 2). Moreover, these gradients impact observed biodiversity patterns. In their study, Cilliers et al. (2013) showed that the previous township areas of Mohadin, Promosa and Ikageng had distinctly less vegetation cover than the town proper and the affluent residential areas (Fig. 7). This is similar to the findings of McConnachie and Shackleton (2010) indicating unequal public green space distribution based on ethnicity and affluence in ten small towns in South Africa. Additionally, affluent areas have higher street tree species richness and densities than poor township areas (Kuruneri-Chitepo & Shackleton, 2011). This pattern was similar for trees and shrubs in domestic gardens studied in Potchefstroom, where low socio-economic status areas had significantly lower woody species densities than the affluent high socio-economic status areas (Cilliers et al., 2013). Woody species were also lower growing with smaller crown diameters in the low socio-economic status areas (Cilliers et al., 2013). Birds studied along the urban rural gradient also indicated patterns corresponding to lower diversity in the poorer township areas, with the exception of higher biodiversity around the Poortjies dam (Fig. 3).The Potchefstroom domestic garden study of Lubbe et al. (2010, 2011) indicated that the total and indigenous species richness of gardens were significantly higher in the high socio-economic classes clearly illustrating the socio-economic gradient in Potchefstroom (Fig. 4).

However, the research carried out on biotope mapping in Potchefstroom (Rost, 2002; Röthig, 2002) revealed the exact opposite trends than those observed for the domestic gardens and birds. A variety of managed and natural open spaces were surveyed indicating that the natural areas in and around the township areas had much higher indigenous species richness patterns (Fig. 5). Interpolation of the percentage indigenous species values of the natural areas and vacant lots in 2012 calculated from paper 3 (in this thesis) indicate the same patterns (Fig. 6). The reason for these contrasting trends is because of the higher species richness of the hills and ridges in rocky grasslands (Mucina & Rutherford, 2006) as well as the fact that the natural areas in the formal municipal commonage area have a shorter history of urbanization influences (Paper 2 in this thesis). Therefore, natural and remnant natural grasslands are not influenced by SES, but rather by anthropogenic urbanization influences in general. This is substantiated by the studies of du Toit (2009) in Klerksdorp (nearby city) and van der Walt et al. (2015a) in Potchefstroom which indicated that species richness of remnant grasslands decrease along an urbanization gradient from rural to urban patches.

Correlation of biodiversity with socio-economic variables is not only limited to South Africa (Martin et al., 2004). The term "luxury effect" was used by Hope et al. (2003) where they correlated family income and housing age with plant diversity in Phoenix, indicating that higher plant diversity is generally found in wealthier suburbs.

The municipal mission statement of the Tlokwe City Council as contained in the IDP is to "provide quality sustainable services that are responsive to our communities' needs within a healthy, safe and green environment through good governance" (Tlokwe City Council, 2014). There was a strong focus on the development of tourism in the area, with the proposed Highveld National Park adjacent to the urban residential boundary (Fig. 8), listed as one of the main tourism infrastructure projects. The most important listed urban greening strategy is a tree planting project that will ultimately result in the planting of 7500 ornamental and fruit trees. This is to redress a commonly observed phenomenon in South African urban areas where poor township areas have very low urban tree densities (Kuruneri-Chitepo & Shackleton, 2011). The study of Cilliers et al. (2013) clearly indicated this trend for Potchefstroom as well (Fig. 7). In the IDP, based on the environmental management plan, areas of high and very high ecological values were determined for the urban area (Fig. 8). The high and very high areas were based on the urban biotope mapping research findings carried out in Potchefstroom (Cilliers et al., 2004; Drewes & Cilliers, 2004; Rost, 2002; Röthig, 2002).

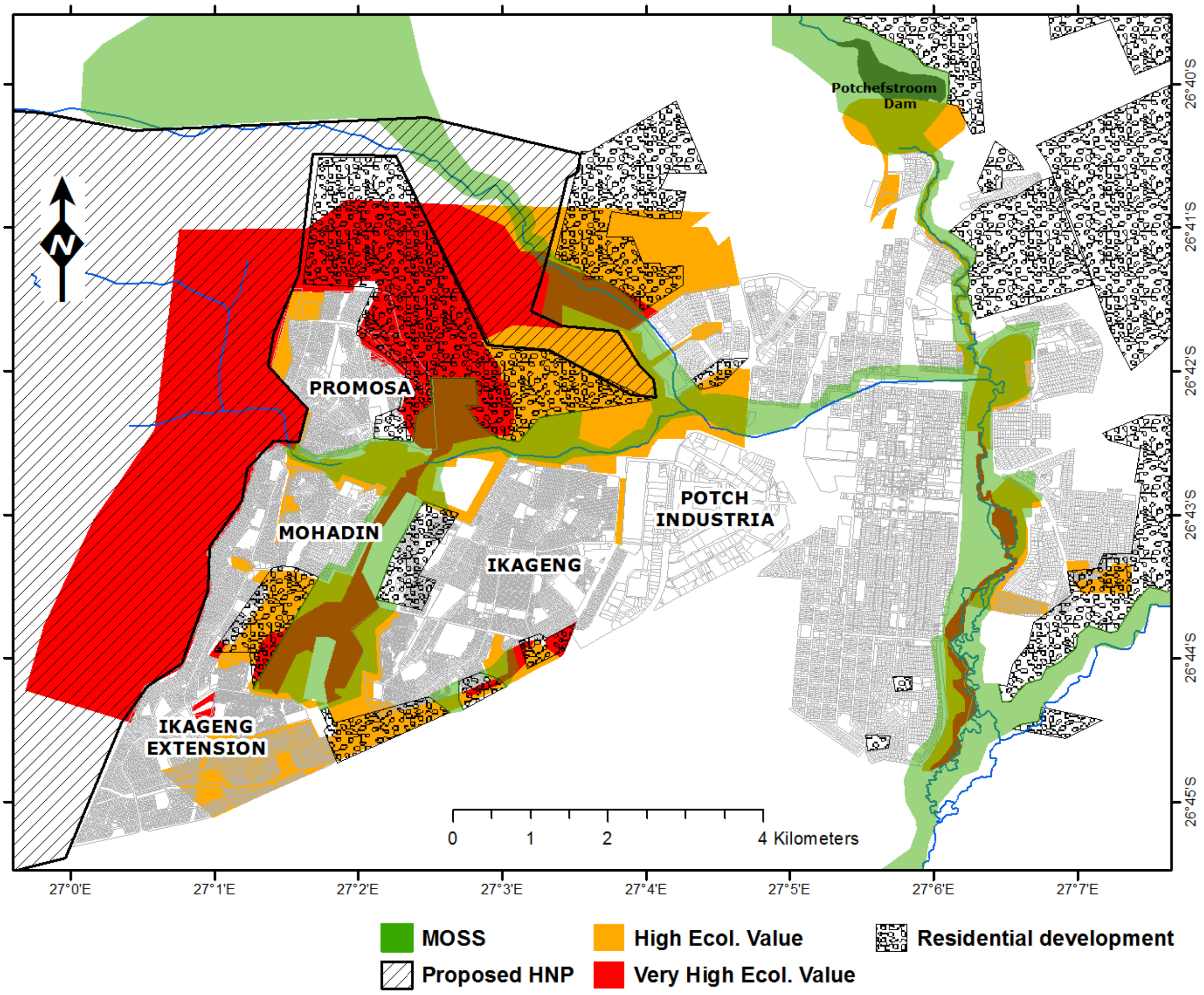

Fig. 8. Map of Potchefstroom indicating the boundaries of the proposed Highveld National Park (HNP), the areas of high and very high ecological value, the proposed municipal open space system (MOSS), and the proposed future residential development areas. Data digitized from the Potchefstroom IDP (Tlokwe City Council, 2014)

These areas mainly include the hills and ridges in the township areas and the banks of the Mooi River as part of the municipal open space system (MOSS) (Fig. 8). The high ecological value of the natural areas around the township areas were also well illustrated in the biotope mapping research (Fig. 5) and the results of paper 3 in this thesis (Fig. 6). Conversely, despite aspiring to "protect the natural, environmental and cultural resources" under the sustainability directive, future residential development is proposed in large parts of these areas (Fig. 8). The spatial vision of the Tlokwe SDF is "to reconstruct the urban framework of Tlokwe in order to create an integrated and sustainable city by focusing on the inherent economic potential the area has to offer" (Maxim Planning Solutions, 2014). The environment forms an essential part of the SDF and within the report is an detailed environmental overview specifically discussing biodiversity, hills and ridges, wetland areas and protected areas within the municipal boundary (Maxim Planning Solutions, 2014). The environmental overview also includes management zones with specific guidelines wherein an urban zone is delineated specifically listing open space/protected areas. The natural resource management guidelines within the urban zone include storm water management, maintenance of ecosystem services, open space provisioning and buffer areas, and the Mooi River. Moreover, the spatial proposals for the urban area specifically include a MOSS wherein protection and rehabilitation of these areas is strongly emphasized. The MOSS includes rivers, streams and wetlands, hills and ridges and the Potchefstroom Dam (Fig. 8). Pollution and refuse dumping together with firewood collection is specifically listed as human impacts affecting the quality of these environments. Intervention strategies are also proposed which include alien species control, rehabilitation programmes and no development in specified areas (Maxim Planning Solutions, 2014). The SDF also includes an environmental protection section as part of municipal wide spatial proposals which lists specific environmental protection management strategies for the reduction of human impacts on natural resources (Maxim Planning Solutions, 2014).

However, despite the large number of urban ecological studies carried out in Potchefstroom (Table 2 and 3), none of them were explicitly mentioned or incorporated in the IDP or the SDF. Moreover, in contradiction, the SDF document acknowledges the lack of ecological data as a major problem in implementing conservation policies as stated by Cilliers et al. (2004). This disregard of existing scientific information is substantiated by Gagné et al. (2015) who stated that science-based information is usually ignored by land use planners. Therefore, in Potchefstroom planners are either unaware of the existence of these studies or they deliberately ignore them. Legislatively, the local municipality is responsible for urban biodiversity protection and management within its administrative boundaries (du Toit & Cilliers, 2015). No relevant bylaws protecting urban biodiversity exist for this municipality. A bylaw is legislation that is passed by a municipal council that is binding in that particular municipality (South Africa, 2000). In Durban, for example, in their parks and recreation bylaw tree preservation orders can be issued by the municipality legally protecting certain trees (eThekwini Municipality, 2015). Despite the asserted importance of the environment in the IDP and SDF, municipal management of these resources inside the urban area is poor. The IDP listed illegal dumping and a lack of awareness as a key constraint. Many municipalities in South Africa also suffer from a lack of capacity and poor implementation of environmental strategies (Wilhelm-Rechmann & Cowling, 2013).

Public opinion

In urban areas natural open spaces are valued in vastly different ways by residents. Most urban open spaces are intensely managed, applauded by most citizens—often to the detriment of biodiversity. Many residents perceive 'wild nature' as poor municipal management (McDonnell, 2007), whilst others see open spaces only as dumping grounds for garden refuse and other household rubbish. There are often conflicting opinions between conservationists and residents of urban areas about exotic tree species in urban areas (van Wilgen, 2012). Urban trees have high aesthetic, recreational and ecosystem service values, which must be traded off against their impact on the local indigenous species. The tree *Salix babylonica* (weeping willow), is the most common woody riverine invader in the grasslands of South Africa (Henderson, 1991). It is naturalized along the watercourses of the north-eastern provinces of South Africa, and as an invader outcompetes indigenous species and can destabilize riverbanks (Henderson, 1991). In Potchefstroom, it dominates the entire course of the river through the urban area. It has high aesthetic value and to many residents in Potchefstroom it is an iconic feature, removal of this tree in urban areas will cause a great public outcry. However, in the specialist study carried out on the Mooi river biodiversity, researchers affirmed that replacement of indigenous vegetation species by weeping willows, amongst other things, highly impacted the original butterfly diversity and riparian vegetation communities (Bouwman, 2005). Additionally, some only view urban open space as undeveloped land—"*environmental issues are seen by many as a preoccupation of wealthy whites and anti-development groups*" (Le Maitre, O'Farrell, & Reyers, 2007) and "*the preservation of nature is regarded as fundamentally in opposition to socio-economic development. Conservation is frequently interpreted as being a socially unjust endeavor, disrespectful toward people and lacking realism*" (Wilhelm-Rechmann & Cowling, 2011).

Sustainable futures?

The largest concern in the evaluation of biodiversity in the context of municipal governance is the disparity between the observed high ecological value of the remaining natural areas surrounding the township areas and their listing as proposed future residential development areas. The results of paper 2 on the effects of urbanization on vegetation indicated that the woody communities found on the hills and ridges of these areas lagged in their response to urban development, indicating the potential extinction debts (Tilman, May, Lehman, & Nowak, 1994) still to be paid in future. Moreover, there were significant declines in the indigenous species richness of these areas over time (Paper 3). Future fragmentation of these areas will surely have detrimental effects on these vegetation communities. Preservation of these areas should be a high priority in municipal planning strategies. Ecologically, it is imperative that more research be carried out on the mechanisms driving these changes to balance future development with conservation goals. On the other hand, the studies of Lubbe et al. (2010) and Botha (2012) indicate the huge contribution of domestic gardens to urban biodiversity. Furthermore, in their study of remnant grassland patches along the urban rural gradient van der Walt et al. (2015a) indicated that grasslands functioned equally well in comparison with exurban patches, emphasizing their conservation value. However, the identified socio-economic disparities in biodiversity patterns need to be address to ensure environmental equity and justice.

We propose that to effectively manage urban biodiversity, all public and private green spaces should be managed collectively as urban green infrastructure. Tzoulas et al. (2007) considers green infrastructure "to comprise of all natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas, at all spatial scales". This is also in line with the recommendation of Cilliers (2009) that effective planning strategies should explicitly incorporate the value of urban green areas to ensure its preservation in urban areas. Urban green infrastructure supplies important ecosystem services (Lovell & Taylor, 2013) and can contribute towards improving human health (Tzoulas et al., 2007). Expressing the value of nature in terms of ecosystem goods and services articulates the importance of conserving nature in a way that can be recognized by decision-makers (Daily et al., 2009). An ecosystem services monetary valuation approach was successfully used in Durban to demonstrate that instead of perceiving open spaces as elitist resources focusing on the requirements of species, open spaces, in fact, provide significant services to humans (Roberts, Boon, Croucamp, & Mander, 2005). Nonetheless, the evaluation of public perceptions towards urban open spaces in Potchefstroom indicated that education of residents is necessary to create awareness, and that participatory approaches should be implemented as a successful strategy to incline residents towards sustainable thinking.

Static protection of existing protected areas is not enough—active and pro-active management approaches are necessary. Ecosystem services should be mainstreamed into municipal governance approaches in a meaningful way that ensures its implementation (Cowling et al., 2008). Despite the recognition and listing of rehabilitation and other management strategies in the IDP and SDF, large areas of the municipal open spaces are severely degraded and refuse dumping is a common occurrence. Policy makers and land use planners need to be made aware of the wealth of ecological data available on Potchefstroom urban environments and meaningful collaborations should also take place between all stakeholders—including scientists. However, a sobering reality is the cost of sustainability oriented management strategies to already constrained municipal budgets. In South Africa where the "poor generally regard environmental problems as something to worry about only when one can afford to do so" (Githiru, 2007), environmental concerns will stay behind other immediate livelihood and service delivery concerns. Scientists need to communicate biodiversity in more effective ways (Wilhelm-Rechmann & Cowling, 2011). Moreover, for the mainstreaming of sustainability in South Africa, scientists of relevant disciplines need to pursue transdisciplinary research goals (Cilliers et al., 2014) and ensure enhanced and timely feedback loops between municipal managers and urban ecologists.

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General Conclusions

"Unlike many other fields of study that wax and wane in their popularity, the study of urban ecology and sustainability will most likely stay "hot" because our present and future depend on it" (Wu 2014).

The general objective of this study was an urban ecological investigation on the state of the science in South Africa with the specific focus on the socio-ecological interactions and dynamics in Potchefstroom. South African urban ecology has made considerable progress from its inconspicuous start in the 1960s, and some of its researchers have produced world-renowned studies (Paper 1: Table 2 and 3). The first paper in this thesis represents the first comprehensive overview of South-African urban ecological publications to date. The second paper was the first to specifically test for time lags in the response of remnant natural vegetation to urbanization in any global city. The third paper represented the first long-term vegetation study in South Africa and quantified how the vegetation composition changed accordingly. Lastly, the fourth paper was the first consolidation of urban ecological data in any one city in South Africa. Each paper addressed one of the specific objectives of this thesis:

To do a comprehensive review of urban ecological research in South Africa and identify gaps in the existing research approaches.

Three hundred and fourteen publications were reviewed and categorized into globally recognized research themes, namely: public participation, human needs, ecosystem services, physical environment, conservation, planning, management, biodiversity, sustainability, and resilience. The publications represent 141 settlements in South Africa (Paper 1: Fig. 1). The cities in which the most research were carried out were Cape Town, Durban, Johannesburg, Potchefstroom, Pretoria, and Grahamstown. The four most common research themes were the physical environment, biodiversity, management, and public participation (Paper 1: Table 4). The article with the highest number of citations was the research carried out on the importance of non-timber forest products to rural livelihoods by Shackleton and Shackleton (2004) (Paper 1: Table 2). Whereas, the article with the highest impact was that of Ernstson et al. (2010) focusing on urban resilience (Paper 1: Table 3). The themes with the most impact in 2013 were management, public participation, planning, resilience, sustainability and ecosystem services (Paper 1: Table 4), indicating the current global themes of importance.

The problems and challenges in South Africa uncovered by the literature study include the management of nature in urban areas as well as the conflict between conservation priorities and societal perceptions and interests (van Wilgen 2012; van Wilgen et al. 2012). Moreover, natural resources are often over exploited and polluted in urban areas with some of the major problems the access to basic services, over-exploitation of water resources, pollution of ground and surface-water resources, health impacts, and water leakage and wastage (Carden and Armitage 2013). Furthermore, local authorities in South Africa have to keep up with increasing urbanization and its negative effect on resources and the resulting socio-economic pressures (Carden and Armitage 2013; du Plessis et al. 2003; Wall 1992). Consequently, environmental issues, including aspects of urban forestry are neglected in budget allocations to address demands for housing and other infrastructure (Kuruneri-Chitepo and Shackleton 2011; Parkin et al. 2006). In general, it appears that South Africa is ill-prepared for the changes that climate change will bring, and is reluctant to take responsibility for its own role in the crisis and implement mitigation measures. Moreover, local government planning practices do not deal effectively with competing land-uses (Cilliers 2009). Development plans often include well versed environmental and sustainable commitments that do not survive the implementation phases, and many housing schemes do not include adequate urban green infrastructure (Shackleton et al. 2014). Moreover, many previously disadvantaged and poor areas have low vegetation cover, no established street trees or small public green spaces (Kuruneri-Chitepo and Shackleton 2011; McConnachie and Shackleton 2010; McConnachie et al. 2008; Schäffler and Swilling 2013).

Another aim of the paper was to identify the research gaps in South African urban ecological literature. These recognized gaps will be discussed as part of the recommendations for future studies. The perusal of the identified gaps and the incorporation thereof with known knowledge will purposefully advance urban ecological research in South Africa.

To determine the effect of the landscape history on the observed vegetation patterns and to quantify potential ecological legacies.

This paper asked three specific questions: (1) do time lags differ for indigenous species and disturbance species richness and between woody and grassland communities and open grasslands? (2) Do these time lags change over time? (3) What are the potential landscape factors driving these changes? Generalized linear modelling was used to determine the potential time lags and the relevant landscape factors. The results indicated that, in Potchefstroom urban grasslands, past histories influenced contemporary vegetation patterns. Woody vegetation showed clear time lags. However, the disturbance species richness had longer time lags than indigenous species (Paper 2: Table 2). The time lag for the indigenous species richness of the woody vegetation was more or less the same for both time periods whilst the disturbance species richness had a ten year difference. In the grasslands, indigenous species richness showed no time lags, and the disturbance species richness changed from 25 to six years (Paper 2: Table 2).

The absence of time lags with a corresponding decrease in indigenous species over the observed time period indicate that grasslands respond faster to anthropogenic effects, or that important mechanisms governing their response was unidentified. The lack of time lags in the open grassland correspond to findings in semi-natural grasslands in Belgium (Adriaens et al. 2006). The newly adapted measure of road network density of natural areas together with altitude were the most frequent predictors in the models (Paper 2: Table 2). However, between the different years some of the measures predicting the different vegetation diversities changed as well as their relationships (positive or negative). The availability of two different vegetation sampling periods is rare, and the aforementioned results on the changes in the behaviour of the measures highlight the danger of making predictions and conclusions based on only the sampling period. However, it must be acknowledged that the measures that were chosen, and the scale (500 m buffer area) of the study can influence the results.

This study was the first one to test explicitly for time lags in an urban environment and corroborates the importance of legacy effects on patterns observed in contemporary communities (Burel 1993; Ewers and Didham 2006). The evidence of time lags and the loss of indigenous species over the 17 year period point towards the existence of potential extinction debts, which is similar to the findings of Hahs et al. (2009) that contemporary cities carry potential extinction debts. The results add to the urgent call to better investigate the drivers and mechanisms responsible for vegetation change (McDonnell and Hahs 2013; Shochat et al. 2006). Moreover, future studies need to test these results with additional measures, different scales, and other cities to determine generalities. Conservation of the remaining grasslands is imperative, especially in the face of climate change and our responsibility towards maintaining sustainable cities and environments in general.

To quantify the temporal vegetation dynamics of the Potchefstroom urban area over a 17-year period.

This paper asked two specific questions: (1) Have the species richness and abundance of species changed within open grasslands, woody vegetation sites, and vacant lots? (2) What are the differences in species composition between these habitats? The results indicated that the species richness increased in the vacant lots from 87 to 139, in both grasslands and woody communities the species richness decreased (Table 2). The mean indigenous species per site increased significantly from nine to 15 in vacant lots (Paper 3: Tables 5 and 8). However, in grasslands and the woody communities the mean indigenous species decreased significantly from 32 to 22 in the grasslands and 27 to 23 in woody communities (Paper 3: Tables 5 and 8). Both the abundance of rare species and the number of dominant species changed in the different habitats over the 17-year period, with many of the rare species in 1995 absent in the 2012 surveys (Paper 3: Tables 6 and 7). The different habitats remained compositionally distinct, however in 2012 some of the grassland sites grouped with the vacant lots indicating the degradation of the grasslands and the increase in species richness of the vacant lots (Table 3: Figs. 3 and 4). The increased percentage in shared perennials of 62% for the grasslands and 63% for the woody communities indicate potential homogenization effects (McKinney 2006). Moreover, the results of the many changes from tree to shrub forms of the woody species indicated the effects of firewood collection on these communities (Paper 3: Table 9). This study was the first long-term urban vegetation study in South Africa and one of the few conducted in temperate natural grassland settings. The results of this study provide additional evidence for the importance of the incorporation of specific temporal site history in the explanation of the differences and similarities in the observed vegetation patterns of sites in urban areas. The presence of time lags (Paper 2) coupled with the significant decreases in indigenous species richness of woody and grassland sites have important consequences for urban grassland conservation in South Africa.

To attempt an interdisciplinary spatial integration and synthesis of all the relevant existing urban ecological research carried out in Potchefstroom to date.

The aim of this paper was to synthesize the urban ecological research carried out in Potchefstroom to determine its value as potential ecological baseline data. Specifically, (1) to combine all the urban biodiversity studies carried out and to compare them with global literature, (2) to identify the gaps in the existing research, and (3) to determine if the steep socio-economic gradient found in Potchefstroom correlated to observed species patterns. This was evaluated against the current municipal IDP and SDF, municipal management strategies, and public opinion to inform progress towards sustainable future scenarios. Potchefstroom has amassed an impressive array of urban biodiversity studies, which included focal studies on vegetation, birds, algae, arthropods, bacteria, aquatic macro-invertebrates, butterflies, reptiles, fish, amphibians and small mammals. The comparability of the results found in Potchefstroom with other global findings, allow valuable additions to determining global urbanization generalizations. Moreover, some of the studies carried out addressed global research gaps, such as the study by Botha (2012) focussing on the comparative diversity of arthropods in vegetable gardens and lawns. Paper 2 of this thesis is also the first urban vegetation study quantifying time lags. The study of van der Walt (2013) was the first to apply landscape functionality analysis in an urban area, whereas the study of Kruger et al. (2015) on amphibian communities was also a first in an African city. However, most of the research focused on vegetation and all other biotic groups are underrepresented. Time frames, seasonality, limited sampling sites all constrain research interpretations.

The results of the correlation of biodiversity patterns with the socio-economic gradient present indicated clear similarities for birds, garden flora and vegetation cover in the urban built up area (Paper 4: Figs. 3, 4 and 7). The natural areas were unaffected by the socio-economic gradient but rather by urbanization influences in general (Paper 4: Figs. 5 and 6). The evaluation of the municipal integrated development plan and the spatial development framework indicated that although biodiversity was specifically incorporated into it, no mention was made of existing literature. We propose that to effectively manage urban biodiversity, all public and private green spaces should be managed collectively as urban green infrastructure. Moreover, the concept of ecosystem services should be mainstreamed into municipal governance approaches in a meaningful way that ensures its implementation (Cowling et al. 2008).

In a South African context were very few municipalities have any ecological data, Potchefstroom stands out. However, the ecological utility of using these results to inform the sustainable discourse will remain limited if continuous monitoring is not carried out and if decision-makers do not incorporate it into municipal management plans. Moreover, for the mainstreaming of sustainability in South Africa, scientists need to ensure enhanced and timely feedback loops between municipal managers and themselves.

Recommendations

In paper 1 specific gaps in the current urban ecological literature were identified. These gaps need to be addressed to ensure a more holistic and comprehensive understanding of South African urban environments. In-depth studies are needed in physical environmental research. Moreover, most of the available literature on urban climates is old and limited to a few cities in South Africa. Research on urban soils is one of the most understudied aspects of urban ecology, whilst most studies on water bodies focus only on rivers; these need to be expanded. Research on pollution of the physical environment also needs attention, specifically by studying it in other cities.

The perusal of the biodiversity theme indicated that vegetation studies dominated and that all the other biotic groups need more attention. Furthermore, comparative studies are needed to allow for the identification of general and unique trends between cities. The call for more mechanistic studies (Shochat et al. 2006) is also a gap in the South African literature. The largest gap identified in management is that better incorporation is needed between science and policy. Additionally, comanagement practices (Graham and Ernstson 2012) need more attention. This links to the need for conservation initiatives to be more socially inclusive, stressing community based approaches which is largely lacking (Ferketic et al. 2010; Graham and Ernstson 2012; Roberts et al. 2012).

Research is lacking in green infrastructure planning (Schäffler and Swilling 2013) and the so-called green value gap (Cilliers 2009). Incorporation of the environment from a planning perspective is needed, leading to the fact that better collaboration is needed between planners and ecologists. The theme of human needs albeit necessary needs to be relativized to better emphasize its importance in contemporary sustainable paradigms. Sustainability themes lack clear delineation and applied goals, and miss the opportunity of sharing expertise between cities. Public participation methods need to include more formal interactions between scientists and citizens to improve transdisciplinarity (Cilliers et al. 2014). Lastly, research on the contemporary themes of ecosystem services and resilience must progress and expand to include more urban areas in South Africa.

The identified vegetation time-lags in paper 2 need to be scrutinized to determine the drivers and mechanisms behind these patterns and repeated to confirm the observed trends.

Continued and expanded monitoring of Potchefstroom biodiversity patterns needs to be carried out in order to enhance its value in sustainable strategies and global comparisons. Scientists and decision-makers should collaborate to ensure the meaningful implementation of existing and future ecological knowledge into management plans. The mainstreaming of ecosystem services through the proposed operational model of Cowling et al. (2008) should be developed and implemented in Potchefstroom to ensure the effective protection and sustained delivery of these services.

Conclusions

The literature review paper formed the background context, informing the current state of urban ecological research in South Africa. The Potchefstroom case study allowed the quantification of the long-term effects of urbanization on vegetation patterns and composition. Moreover, synthesizing all available literature for Potchefstroom allowed insights into how urban ecological knowledge is translated into municipal management plans and strategies. The results of this thesis can form a meaningful contribution towards the advancement of urban ecology in South Africa and the world.

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