Baseline assessment of the density and diversity of birds around Matimba and Medupi power station

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NOORDWES-UNIVERSITEIT

It all starts here ™

PREFACE

Format of dissertation

The research is presented in the article format and the researcher intends to submit the article for publication in *Ostrich: Journal of African Ornithology*. It should be noted that the formatting, style of referencing, figure and table numbering and general outline of the article is presented according to the guidelines of this journal. For clarity, all references used in the article were listed again at the end of the dissertation in the correct style, according to the guidelines of North-West University.

Outline of dissertation

This dissertation is presented in four chapters and a description of each chapter is provided below:

Chapter 1: Introduction

This chapter includes the specific problem at hand and motivation regarding the study. The aim and objectives, and hypothesis of the study are also included in this chapter.

Chapter 2: Literature review

This chapter provides a background to pollution impact studies and looks at sulphur dioxide as a pollutant. The importance of birds in biodiversity conservation and the role of geospatial technologies in avian studies are outlined in this chapter.

Chapter 3: Article

The chapter comprises of an article which focuses on exploring the relationship between bird communities and sulphur dioxide air pollution. The article gives descriptions of the density and diversity of birds and investigates the environmental variables affecting avian biodiversity in the environs of Matimba and Medupi power station.

Chapter 4: Conclusion, limitations and recommendations

This chapter discusses the conclusions of the study and highlights important findings from the study. This chapter also examines the limitations to the study and provides recommendations for future research.

This study was planned and implemented by a team of researchers. The contribution of each researcher is described in Table 1.

Table 1: Research team and contributions.

Name	Contribution
Mr. L. Muyemeki	Masters research student, responsible for implementing the research process, collecting data, compiling and completing the dissertation.
Prof. Dr. S. J. Piketh	Supervisor, critical reviewer of the study and the article
Dr. S. W. Evans	Co-supervisor, critical reviewer of the study and the article
Mr. R. Burger	Assisted in the modelling of ambient sulphur dioxide

DECLARATION

I hereby declare that I have approved the article and that my role in the study as indicated above is representative of my actual contribution. I hereby give consent that this article may be published as part of Luckson Muyemeki's M.Sc (Geography and Environmental Management) dissertation.

Prof. Dr. S. J. Piketh

Dr. S. W. Evans

Mr. R. Burger

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"The increase of scientific knowledge lies not only in the occasional milestones of science, but in the efforts of the very large body of men who with love and devotion observe and study nature."

- Polykarp Kusch -

ABSTRACT

Bird populations are changing at unprecedented rates in response to human-induced changes to the global environment, and these rates of change are expected to accelerate over the coming decades. Changes in the levels of sulphur dioxide (SO_2) in the atmosphere through emissions from power stations pose a potential threat to bird populations. However, avian response to SO_2 pollution is poorly understood. Exploring the relationship between avian diversity and SO_2 exposure levels will help in determining species sensitive to air pollution.

This study seeks to understand the interactions between avian diversity and SO_2 concentration levels around Matimba power station so as to have more insight on the level of avian vulnerability to air pollution. Matimba is an important site in South Africa as a second coal fired power station, Medupi, is currently being constructed with additional stations also a possibility. This study represents an important baseline assessment of the avian population status before the additional pollution burden is realised from Medupi.

Ten min repeated point counts were conducted at three sample sites with varying distances from Matimba and Medupi power stations. These counts were used to calculate bird species density and diversity. Cloud-free Landsat 8 imagery acquired on 7 January, 2014 was used to derive habitat structure and productivity variables. Elevation variables were derived using a DEM (Digital Elevation Model) obtained from NASA Global Data Explorer. The AERMOD dispersion model was used to characterise spatio-temporal variations in ambient SO_2 concentrations around Matimba power station. Multiple regression analysis was then used to ascertain which of these variables (SO_2, habitat structure, productivity and terrain) contribute most to the observed variation in bird species density and diversity around Matimba and Medupi power stations.

SO_2 polluted air did not have an influence on bird species density and diversity at the community level. At species level two species (*Batis molitor* and *Streptopelia senegalensis*) exhibited some measure of negative response to SO_2 air pollution. However, after further investigation using multiple regression analysis it was revealed that habitat structure had more influence on the density of these two species compared with ambient SO_2 concentrations. Bird species density and diversity varied significantly among the sample sites but were not related to the distance to the source of the SO_2 air pollution.

Evidence obtained from this study revealed that continuous monitoring of the interactions between SO_2 polluted air and bird populations is recommended for a more comprehensive understanding of avian susceptibility towards SO_2 air pollution and this will also facilitate in the selection of sensitive and relevant species for future ecology studies at other coal-fired power stations. Furthermore, it is expected that SO_2 concentrations will significantly increase with the commissioning of Medupi power station thus further necessitating the need for continuous monitoring of bird species densities around Matimba and Medupi power stations.

Key words: air pollution, sulphur dioxide, species density, species diversity, power stations

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CHAPTER 1 INTRODUCTION

1.1 Problem statement and motivation

Coal plays an important role in the South African energy sector as it is the largest source for electricity generation contributing nearly 70% of the country's primary energy (Winkler, 2006). Coal is inexpensive and readily available in South Africa, therefore there are huge economic and socio-political incentives to construct more power plants as demand for electricity rises in the country (Shindell & Faluvegi, 2010). This however has raised concerns about the potential environmental risks that might result from constructing more power stations as coal is the most polluting energy source to the atmospheric environment in South Africa (Winkler, 2006).

Globally, 70-80 million tonnes of sulphur dioxide (SO_2) is released per year due to human activities (Raheem *et al.,* 2009). Fossil fuel burning contributes to 80% of the anthropogenic SO_2 and 75% of this fossil fuel burned is from coal (Friend, 1973; Raheem *et al.,* 2009). SO_2 emissions into the atmosphere from coal fired power plants are a major health concern to humans causing or exacerbating asthma and bronchiolar constriction (Turco, 2002). SO_2 is also one of the main precursors of acid rain which can lead to the acidification of forests, soils and lakes as well as damage to crops (Adekola *et al.,* 2012). Given these setbacks from coal burning, the major dilemma which the coal fired power industry faces is how to continually deliver the various economic and social benefits of coal whilst at the same time reduce the negative environmental effects associated with its use (Mbohwa, 2013).

Birds are species of ecological significance that are well monitored around different regions as they are taxonomically known and easily detectable. Birds perform a broad array of ecosystem services ranging from pollination and seed dispersal to pest and disease control i.e. vultures play a vital task of removing disease from the ecosystem through consumption of carrion (Sekercioglu, 2006; Whelan *et al.,* 2008). Avian populations are changing rapidly as a result of extensive environmental change and these rates of change are expected to accelerate over the coming decades (Gregory *et al.,* 2009). At the current rate of change it is predicted that half of the world's bird species are likely to go extinct in the next 200-300 years (Smith *et al.,* 1993). Anthropogenic activities are the main driver of these bird population declines and such activities are still ongoing despite international consensus that biodiversity loss must be arrested (Butchart *et al.,* 2010). Understanding ecological factors that control the stability and persistence of bird populations is therefore crucial in establishing conservation strategies that will mitigate the adverse impacts of human activity (Liu *et al.,* 2013).

Air pollution is a phenomenon that is gaining increasing attention in avian studies (Eava *et al.,* 2002). Birds function as early warning systems (de Villiers, 2009). Due to their high sensitivity to subtle changes in the environment they are often considered good indicators of environmental pollution (Chambers, 2008). Research on air pollution related impacts on birds date back to the second half of the 20^{th} century and have demonstrated the harmful effects of air pollution (e.g.; Ratcliffe, 1967; Cooke, 1973; Furness, 1993). However, investigative efforts on birds focused mainly on examining the effects of heavy metal emissions on the breeding performances of individual bird species (Belskii *et al.,* 1995; Eava *et al.,* 2009; Berglund & Nyholm, 2011).

Coal burning power plant emissions of SO_2 into the atmosphere pose a potential threat to birds, however, little is known on bird population dynamics around coal-fired power stations (Treissman *et al.,* 2003). To date, few attempts have been made to investigate avian population responses to SO_2 air pollution. Globally, air pollution has contributed to a decline in bird populations however, due to the intricacy of the atmosphere it is difficult to establish whether the reported outcomes of air pollution on birds are due to exposures to SO_2, other pollutants, or a combination of SO_2 and other pollutants (Treissman *et al.,* 2003). This presents a major challenge to conservation as management options are limited.

There is need for comprehensive analyses on the association between ambient emissions and changes in the bird populations as this will give more insight on the level of avian vulnerability to air pollution (Eava *et al.,* 2012). To the best of our knowledge attempts to link bird population density changes with SO_2 pollution from coal fired power plants have not been carried out or documented in South Africa. Therefore this study will help in understanding the interactions between bird population densities and SO_2 concentration levels around coal-fired power stations.

1.2 Aims and objectives

The aim of the research was to examine the relationship between bird populations and the concentrations of SO_2 in the air around Matimba and Medupi power stations. The main objectives were as follows:

- Determine the species diversity and density of birds within a 25km radius of Matimba and Medupi power stations
- Determine the environmental variables that affect the bird populations within a 25km radius of Matimba and Medupi power stations
- Determine the current influence of SO_2 polluted air on bird population density and species diversity prior to the commencement of operations at Medupi power station

- Establish a baseline against which future studies can assess the influence of SO_2 air pollution on birds once Medupi power station is fully operational

1.3 Hypothesis

SO_2 emitted from Matimba power station does not affect the species diversity and density of birds around the power station

1.4 References

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CHAPTER 2 LITERATURE REVIEW

2.1 Ecology of the impact region

Changes in the structure and function of ecosystems stimulated by industrial pollution have been taking place since the industrial revolution. These changes came under scrutiny from ecologists in the late 19th century (Holland, 1888). Research on pollution related effects on biota occurring in contaminated areas have exposed the undesirable outcomes of pollution. These studies were performed within the vicinities of point polluters e.g. large industrial enterprises (ferrous and nonferrous smelters, cement plants and coal-fired power stations) which emit pollutants in the form of sulphur dioxide, nitrogen dioxide or heavy metals (copper, lead, aluminium, nickel, zinc). Such studies carried out within the precinct of point polluters give descriptions of dead forests and "moonscapes" as evidence of the adverse effects of industrial pollution on biota (Freedman, 1989). However, it is now becoming more apparent that the effects of pollution from point polluters are not all negative, conditions created by industrial pollution have allowed for other forms of biodiversity to flourish (Batty & Hallberg, 2010). These organisms that have genetically adapted to the conditions of the polluted sites can potentially be used in the remediation of other contaminated sites (Batty & Hallberg, 2010). Understanding how organisms or communities within ecosystems respond and adapt to pollution exposure is therefore of central concern to modern ecology (Kozlov & Zvereva, 2011). However, given the complex interactions taking place within ecosystems the main challenge for ecologists is to understand the factors influencing the resilience of communities and ecosystem functions (Moretti *et al.,* 2006).

In an attempt to address all the aspects associated with point polluters and their effects on the environment, Vorobeichik (2004) proposed a new scientific field of study known as impact ecology or ecology of the impact region. It encompasses an integrated approach towards monitoring and analyzing ecosystem alterations within impact regions resulting from industrial pollution. An impact region according to Vorobeichik & Kozlov (2012) is the area surrounding a point polluter varying in spatiotemporal scale and exposed to the effects of industrial pollutants (mainly from atmospheric emissions). The demarcation of an impact region is difficult to define but more often than not it is found in the zone where distinction between the influence of the point polluter and the influences of environmental variables is no longer plausible (Vorobeichik & Kozlov, 2012).

Pollution studies carried out on different impact regions are distributed unevenly between continents (Table 2–1). The northern hemisphere dominates with more than half of these studies found in Europe while in the southern hemisphere there is a huge knowledge gap with only 3 point polluters having been investigated.

Table 2–1: Distribution of the studied point polluters by continents and countries (adapted from Vorobeichik & Kozlov, 2012).

Continent	Country
Europe	Russia (43), Poland (23), Ukraine (13), Belarus (6), Slovakia (5), Bulgaria (4), Lithuania (4), Czech Republic (4), Great Britain (3), Finland (3), Austria (2), Germany (2), Sweden (2), Estonia (2), Denmark (1), Iceland (1), Latvia (1), The Netherlands (1), Slovenia (1), France (1)
Asia	Russia (18), India (13), Turkey (5), Kazakhstan (2), Japan (2), Georgia (1), Jordan (1), Pakistan (1), Taiwan (1), Uzbekistan (1), South Korea (1)
America	Canada (17), United States (17), Brazil (1), Chile (1)
Africa	Egypt (1)
Australia	Australia (1)

2.2 Birds as biological indicators

The earth has undergone rapid environmental changes as a result of anthropogenic activities such as mining, agricultural expansion and urbanisation (Tilman and Lehman, 2001). A major consequence of human changes to the environment is biodiversity loss. It is a form of global change that is the most difficult to reverse and affects numerous taxonomic groups (Novacek & Cleland, 2001). Human modifications to the earth have created environmental conditions that limit the abundance of both terrestrial and aquatic species, and this will inevitably lead to global species extinctions (Tilman & Lehman, 2001). In 2002 world leaders met at the World Summit on Sustainable Development and set global and regional targets to significantly reduce the rate of biodiversity loss by 2010. In order to achieve such targets consistent and effective monitoring of environmental conditions through quantification of all ecosystem properties is required (Chambers, 2008). However due to the complexity of the ecosystem, a holistic approach towards monitoring biological diversity is unrealistic and also time intensive and costly (Mikusiński & Angelstam, 1997).

A more pragmatic approach of assessing biodiversity in the absence of comprehensive data on ecosystems is through monitoring a set of biological indicators (Gregory & Strien, 2010). Chambers (2008) defines a biological indicator as: "*A species whose characteristics (e.g. presence or absence, abundance, density, mortality rate, breeding success) indicate the condition of ecosystems, the status of other taxa, the presence and impacts of stressors, or patterns of biological diversity"*. These indicators can be used to determine the status of a variable in the environment that has not been measured. Biological indicators can also be used to identify and communicate intricate phenomena such as biodiversity trends and patterns in a more simplistic manner (Bibby, 1999). This helps policy decision makers to prioritize their strategies and practices on biodiversity conservation (Smeets & Weterings, 1999). Although effective as they are, biological indicators have their limitations too. Information on a particular indicator species is not always readily available and more often than not is hard to obtain. Some indicator species profit from environmental change while others do not and predicting such behaviours can be difficult (Gregory & Strien, 2010).

For biological indicators to be effective they need to meet a set of requirements that are often conflicting (Hilty & Merenlender, 2000). These requirements include: (1) In order for an environmental variable or variables of interest to be investigated through trend patterns in an indicator species, it is essential that this biological indicator is sensitive to changes taking place to the environmental variable or variables (Simberloff, 1998). (2) These species must be easy to detect and count so that monitoring data are obtained in a reliable and repetitive manner (Chambers, 2008). The aforementioned attributes are fundamental in the selection of suitable biological indicators in any environmental monitoring programme.

There are a number of reasons that qualify birds as useful biological indicators. Birds are conspicuous creatures that are relatively easy to detect and comparatively easy to survey (Carignan & Villard, 2002). They are ecologically versatile occurring in a wide range of terrestrial and marine habitats across all continents (Gregory & Strien, 2010). Birds occur across a wide range of trophic positions thereby making them sensitive to subtle changes at different levels of the food chain i.e. they are responsive to environmental pollutants such as persistent organochlorines that accumulate at every level of the food chain (Mac Nally *et al.,* 2004; Gregory *et al.,* 2005). Therefore, birds are considered good indicators of pollution related changes to the ecosystem (Metcheva *et al.,* 2011). The techniques used to survey birds are relatively simple and well developed with the counts being fairly inexpensive to conduct, particularly when experienced and motivated volunteers gather the avian data (Koskimies, 1989; Gregory & Strien, 2010).

Although the above mentioned attributes are substantially favourable for birds as suitable indicator species, birds also possess negative features that diminish their value as biological indicators. (1) Avian species respond more to secondary changes in the environment rather than primary changes e.g. Eeva *et al.* (2010) observed that the decline in the abundance of snails with calcium rich shells in the copper polluted area of Harjavalta, Finland created reproductive problems for the Pied Flycatcher (*Ficedula hypoleuca*) which relies on snails for calcium during breeding. This attribute found in birds delays their response to environmental stressors that by the time the problem is identified it is difficult to alleviate or reverse (Morrison, 1986; Koskimies, 1989). (2) Birds compared to other taxa are highly mobile. Their movements and migratory patterns makes it difficult to connect responses of birds to specific environmental conditions in a particular area as their population dynamics are more of a response to an integrated set of environmental variables from across large and varied regions (Gregory *et al.,* 2005; Gregory & Strien, 2010). However, on the other hand, this could be seen as a positive characteristic in that the response to change can be rapid.

2.3 Coal-fired power stations

The coal-fired power industry is the largest contributor to global electrical power (Shindell & Faluvegi, 2010). Approximately 41% of electricity worldwide is generated through coal-burning at power plants (Shindell & Faluvegi, 2010). Coal burning power plants are currently the least expensive option for generating electricity. However coal fired power stations are also major contributors to global environmental change through emissions of pollutants mainly in the form of sulphur dioxide gas which have resulted in harmful effects to both human health and the environment (Oman *et al.,* 2002). Despite the adverse effects of coal-fired power plants and the major improvements in renewable energy use, it is predicted that coal and other fossil fuels will remain the dominant energy sources in the near future (Smouse *et al.,* 2000). Therefore there is need for abatement technologies that will improve the environmental performance of coal burning power plants.

2.4 Matimba power station

Matimba is a coal-fired power plant owned by South Africa's publicly-owned electricity utility Eskom. Due to environmental concerns about the air pollution levels around Witbank where most of Eskom's power plants are situated and also due to the large reserve of coal deposits in the Lephalale area, Matimba power station was positioned near Lephalale. It is the biggest direct dry-cooled power station in the world. The station was designed as a dry-cooled power station because of a shortage of water within the Lephalale area. Construction of Matimba power station began in 1981 and operations commenced in 1986. The power plant has a base generation capacity of 3990 Megawatts (MW) comprising of 6 x 665 MW pulverised fuel boilers which were commissioned between 1987 and 1991. Matimba power station acquires its coal from Grootegeluk Colliery mine through a system of conveyor belts which are between a distance of 10.7 km and about 12 km long. The mine has sufficient coal reserves to assure Matimba a minimum lifespan of 35 years at 3800 tonnes of coal per hour. Electrostatic Precipitator and Flue Gas Condition Plants (SO_3) were installed in Matimba power station to reduce particulate emissions. Currently there is no SO_2 emission control equipment installed at Matimba.

Figure 2-1: Matimba power station.

2.5 Medupi power station

Medupi is an Eskom owned, dry-cooled coal-fired power plant which is currently under construction. The power station is strategically positioned in the west of the Lephalale area in close proximity to Matimba power station so as to benefit from the easily accessible coal resources and to facilitate connection to the existing Eskom power grid. The new power plant will comprise of 6 x 800 MW boiler units with a total base generation capacity of 4800 MW. Construction of the power plant began in May 2007 and on 2 March 2015 the first unit (Boiler 6) was synchronised to the national power grid. Medupi power station will utilise pollution abatement technologies so as to improve environmental performance. These technologies include pulse flue gas desulphurisation (which will reduce SO_2 emissions by over 90%), jet fabric filters (which will remove over 99% of particulate matter) and low NO_x burners. The power plant will acquire its coal supply through a brownfields expansion of Grootegeluk Colliery mine with mining from the present opencast pit continuing at an accelerated rate.

Figure 2-2: Medupi power station.

2.6 Sulphur in coal

Sulphur in coal generally originates from parent plant material making up the original peat (accumulation of partially decayed vegetation matter) (Tzimas *et al.,* 2007). The concentration of sulphur in coal is controlled mainly by the age of coal and type of soil or rocks accompanying its formation (Kalenga, 2011). Sulphur in coal exists in both organic and inorganic forms. Inorganic sulphur constitutes the major ash content in coal and consists mainly of pyrite (FeS_2) which occurs in two crystalline habits: pyrite (cubic) and marcasite (orthorhombic), with the former being more common (Kalenga, 2011; Adekola *et al.,* 2012). Pyrite crystals are randomly distributed throughout the coal but their particles are not bound to it.

Organic sulphur compounds are commonly grouped into thiophenes (methyl thiophene, dibenzothiophene, ethyl thiophene), mercaptans (methylthiol, naphthalene thiol) and sulphides (dibenzyl sulfide) (Kalenga, 2011). Their presence in coal is dependent on the level of biochemical conversion of the peat, temperature and pressure conditions, as well as the mineral forms concerned with the formation of coal (Meyers, 1982; Selsbo, 1996). Physical or chemical removal of organic sulphur in coal is difficult as it forms part of the coal organic structure through covalent bonding (Adekola *et al.,* 2012).

2.7 SO_2 as a pollutant

SO_2 is a colourless, non flammable gas with a suffocating, pungent odour (Budavari, 1996). Ninety five percent of sulphur present in coal is released as SO_2 into the atmospheric environment during coal combustion (Franco & Diaz, 2009). Once present in the atmosphere, SO_2 can be oxidized to sulphur trioxide (SO_3) through photolytic and catalytic processes involving ozone (O_3), nitrogen oxides (NO_x), and hydrocarbon (HC), leading to the formation of photochemical smog (Dara, 2006). SO_2 is removed from the atmosphere either as wet deposition when SO_3 reacts with water vapor to produce droplets of sulphuric acid (H_2SO_4) and is released into the biosphere as acid rain. As dry deposition, SO_2 settles onto the terrestrial ecosystem in its gaseous state (Treissman *et al.,* 2003). SO_2 can also react with volatile organic compounds (VOCs) under conditions of high humidity and elevation to form sulphonates such as alkane sulphonates (Kylin *et al.,* 2010).

The main route of exposure to SO_2 gas for humans and animals is through inhalation. In the moist upper respiratory tract, 40 to 90% of inhaled SO_2 is absorbed and rapidly converted to sulphuric acid (Raghunandan *et al.,* 2008). Due to its acidity, sulphuric acid can result in the irritation and inflammation of respiratory tissues. Inflammation of the respiratory tract can lead to shortness of breath, coughing, mucus secretion, chronic bronchitis and asthma aggravation among asthmatic individuals (Khan & Siddiqui, 2014). Acute exposure to SO_2 can have adverse health effects on livestock. Mild bronchial constriction, metabolism changes, and irritation of the respiratory tract and eyes in cattle are among the reported symptoms found in livestock exposed to SO_2 (Coppock & Mostrum, 1997). Sensitive (allergic) sheep that were exposed to four hours of 5 ppm (13.25 mg/m^3) of SO_2 exhibited an increase in airway resistance (Abraham *et al.,* 1980).

Injury to plants is a major consequence of SO_2 air pollution (Winner *et al.,* 1985). To plants SO_2 is essentially a phytotoxic gas causing chronic or acute foliar damage (Swain & Padhi 2013). When SO_2 enters plants through the stomata by processes of photosynthesis and respiration, it reacts with water on the cell walls inside the leaves producing sulphuric acid which reacts with other compounds present in the leaves and are transferred to different parts within the plants (Zhang *et al.,* 2013). High concentrations of SO_2 present in plants can lead to foliar necrosis which reduces biomass production and yield, and quickens senescence (Swain & Padhi 2013; Zhang *et al.,* 2013).

2.8 Potential impacts of SO_2 on birds

Literature on air pollution and avian biodiversity is primarily centered on heavy metal emissions, focusing on heavy metal pollution impacts on bird breeding performances (Eeva *et al.,* 2012). Knowledge on the possible effects of SO_2 pollution on the bird populations is lacking. Birds have high metabolic rates, and have the potential to be affected directly and indirectly by ambient SO_2 pollution. In Czechoslovakia, in 1977, unreported concentrations of SO_2 negatively affected nesting in house martins (*Delichon urbicum*) resulting in martins avoiding polluted nesting areas in favour of unpolluted nesting areas (Newman, 1979). A study carried out by Kylin *et al.* (2010) looking at the possible effects of SO_2 on bird feathers found that elevated concentrations of sulphonates in the atmosphere could affect the water repellence of Blue Swallow (*Hirundo atrocaerulea*) plumages, resulting in the water droplets more easily penetrating their feathers so impacting them by possibly reducing their capability to forage.

Indirectly SO_2 can affect the food chain of birds through the acidification of surface waters e.g. the decline in the abundance and reproductive success of the Dipper (*Cinclus cinclus*) along acidified streams in Great Britain was attributed to a decrease in the abundance of their main prey (mayflies, caddisflies, and amphipods) resulting from a negative response to stream acidification (Ormerod *et al.,* 1991).

The aforementioned impacts of SO_2 on avian biodiversity serve as motivation for more comprehensive studies to be conducted that will give a more informed understanding about primary and secondary responses by birds towards exposure to SO_2 air pollution.

2.9 Role of Geographic Information Science and Remote Sensing in avian studies

Effective monitoring and accurate mapping of avian biodiversity patterns over broad spatial scales is difficult to achieve. On-the-ground monitoring of avian communities is expensive, time consuming and limited to small spatial scales (Ralph *et al.,* 1995; St-Louis *et al.,* 2006). Remotely sensed imagery and Geographic Information Systems (GIS) technologies offer easier, quicker and cheaper alternatives for characterizing bird distributions and predicting avian habitats over broad landscapes (Gottschalk *et al.,* 2005). The ability to use GIS to examine spatial patterns as well as the repetitive synoptic perspective and temporal frequency of remotely sensed data allows for the monitoring of avian communities at different spatial and temporal scales (Miller & Rogan, 2007).

Bird conservation planning has progressively become more reliant on remote sensing and GIS (Johnson & Winter, 2005). With the increased availability of geospatial information (i.e. topographical, biological and climatic data) these analytical tools now play more critical roles in conservation through the production of models used to predict the occurrence of individual bird species, avian species richness and density at large spatial scales (Culbert *et al.,* 2012; Wood *et al.,* 2013). In Spain, for example, ecological niche modelling was used to predict the spatial distribution of the Short-Toed Eagle (*Circaetus gallicus*) in relation to the potential availability of its prey (Niamir, 2009). In the Chihuahuan desert of New Mexico, Landsat derived texture measures and vegetation indices were used to explain the pattern of bird species richness (St-Louis *et al.,* 2009).

2.10 Ecological baseline surveys

Ecological Baseline surveys are studies conducted to determine the biological conditions of a development project site and its environs. They provide an information base against which to monitor and assess an activity's biological impact during operation and after the activity is completed (IAEA, 2005). These surveys offer an opportunity to evaluate how biological conditions of the environment were to develop in the absence of a project. Ecological baseline surveys can be classified into soil baseline surveys, vegetation baseline surveys and wildlife baseline surveys (EPA, 2000).

Soil baseline surveys seek to characterize the soil conditions in a defined study region at and around the project site through mapping of soil types and depth as well as through description and inspection of the metal content of the soil (Deckers *et al.,* 2004). Vegetation baseline surveys aim at describing the plant conditions in a defined study region at and around the project site through vegetation description and mapping (de Castro, 2010). A wildlife baseline survey seeks to describe the terrestrial species present, habitat use, relative abundance and distribution in a defined study region at and around the project site (EPA, 2000)

2.11 Legislation on biodiversity conservation and air quality

The National Environmental Management Act (NEMA) (Act 107, 1998) is the main legislation by which South Africa's environment is managed. It is a primary environmental framework Act which provides a set of principles for decision making with regards to activities that affect the environment and promotes co-operative governance. The National Environmental Management: Protected Areas Act, 2004 (Act 57 of 2004), the National Environmental Management: Biodiversity Act, 2004 (Act 10 of 2004) and the National Environmental Management: Air Quality Act, 2004 (Act 39 of 2004) are the environmental statutes that have been designated under the NEMA framework. Crooning

The National Environmental Management: Biodiversity Act, 2004 (Act 10 of 2004) promotes the conservation of plant and animal biodiversity, including the soil and water upon which they depend. This should be achieved through protection of species and ecosystems, sustainable use of local biological resources, fair and equitable sharing of benefits arising from bioprospecting concerning indigenous biological resources and the establishment of a South African National Biodiversity Institute. Under this Act the Minister of Environmental Affairs and Tourism is required to prepare and implement a National Biodiversity Framework, which provides for the identification of priority areas for conservation, as well as an integrated, coordinated and uniform approach to biodiversity management in protected areas. The Act also encourages the publication of provincial and national lists of ecosystems that are threatened and in need of protection e.g. critically endangered ecosystems, endangered ecosystems, vulnerable ecosystems, protected ecosystems.

The National Environmental Management: Air Quality Act, 2004 (Act 39 of 2004) serves to revoke the Atmospheric Pollution Prevention Act (45 of 1965) and various other legislations dealing with air pollution. According to the Act, the Minister of Environmental Affairs and Tourism and the members of the Executive Council of a province (MEC) has the mandate to issue standards, enforce regulations and other measures. It also stipulates them to implement penalties for non-compliance and to establish funding arrangements. The purpose of the Act is to set norms and standards that will: protect, restore and enhance the air quality in South Africa; increase public participation in the protection of air quality and improve public access to relevant and meaningful information about air quality; and reduce the risks to human health and prevent air quality degradation. The Act is responsible for the establishment of national ambient air quality standards. These standards ensure the protection of the environment and human health through enforcement of regulations and continuous monitoring of pollutants.

2.12 Conclusion

The purpose of this chapter was to provide a comprehensive outline of the literature considered important in understanding the importance of birds in biodiversity conservation and how air pollution is a threat to birds. The chapter also focused on the role of geo-spatial technologies (i.e. remote sensing and GIS) in mapping and monitoring avian biodiversity patterns, as well as legislation pertaining to biodiversity conservation and air quality.

The following conclusion was derived from the literature review: although the notion of using indicator species to monitor changes to the environment is alluring to conservation planners, the effectiveness of birds as indicators of environmental health is still debatable (Carignan & Villard 2002; Lindenmayer & Burgman 2005). Birds are only useful in measuring a component of biodiversity change and care must be taken when making conclusions based on a single group of species (Gregory & Strien, 2010). Interaction

Monitoring avian diversity changes around coal-fired power stations is important in understanding avian responses to varying levels of SO_2, however, due to the complexity of the ecosystem relevant conclusions can only be reached by applying methods that allow researchers to collect data suitable for solving practical questions related to ecosystem changes under conditions of rapid industrial development (Vorobeichik & Kozlov, 2012).

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CHAPTER 3 ARTICLE

Baseline assessment of the density and diversity of birds around Matimba and Medupi power station

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ABSTRACT

The expansion of coal fired power stations in South Africa has resulted in growing environmental concerns as they are the largest emitters of sulphur dioxide (SO_2). These emissions from power plants pose a potential threat to avian populations, however, the effect of SO_2 pollution on bird communities is poorly understood. Using point counts we investigated the relationship between bird species density/diversity and SO_2 concentrations around Matimba and Medupi power stations. Environmental parameters were derived from remotely sensed data and analysed together with variation in SO_2 concentrations using multiple regression analyses. We also tested whether the observed bird species density/diversity varied between different sample sites. Our findings revealed that variations in species density and diversity were not correlated to the SO_2 concentration levels around Matimba. In addition, both species density and diversity varied significantly among the sample sites but were not related to the distance to the source of the SO_2 air pollution. Of 27 species, only two species were negatively correlated to SO_2 air pollution, however, the effects of SO_2 were less significant than the influence of habitat structure. Further monitoring of avian diversity changes around the power stations is recommended as this will facilitate in identifying species sensitive to SO_2 pollution.

3.1 Introduction

Many bird species in South Africa are under significant pressure from anthropogenic activities that threaten their local survival (Barnes 1998). Disturbances to ecosystems through agricultural expansion, mining and environmental pollution create stresses on bird populations as avian habitat is either converted, destroyed or fragmented (BirdLife International 2008). Approximately

10% of all African bird species are facing global risk of extinction (BirdLife International 2013). Between 2005 and 2012, 25 bird species were up-listed to higher threat categories in the IUCN Red List and only seven species were down-listed (BirdLife International 2013). Environmental pollution is a main threat to birds affecting more than one-fifth of threatened birds in Africa through air-borne pollutants, agricultural and industrial effluents (BirdLife International 2013).

Prominent examples of the lethal effects of pollution on birds in South Africa include the population decline of the African Penguin (*Spheniscus demersus*) in South Africa due to oil pollution from the Apollo Sea oil spill of 1994 and the Treasure oil spill of 2000 which resulted in over 30 000 individuals being killed (Birdlife International 2013, Crawford et al. 2000, Underhill et al. 1999). Another example is the intentional and inadvertent pesticide poisoning of Blue Cranes (*Anthropoides paradiseus*) by farmers in South Africa resulting in as many as 600 Blue Cranes being killed in a single event (Johnson 1992). Use of dichlorodiphenyltrichloroethane (DDT) and other insecticides for Malaria control has sub-lethal effects on birds. Investigations in the Limpopo province of South Africa reported very high levels of DDT in Grey Heron (*Ardea cinerea*) eggs (13 000 ng/g wm) which surpassed the critical levels associated with impaired reproductive success in Brown Pelicans (*Pelecanus occidentalis*) (Bouwman et al. 2013). Considerable egg shell thinning in Cattle Egrets (*Bubulcus ibis*) was also reported in this region (Bouwman et al. 2013).

Industrial air pollution is gaining increasing attention in avian studies. It encompasses the emission of substances into the atmospheric environment that are damaging to both life (human, animal or plant) and property. Studies have shown that industrially polluted air has negative effects on bird population densities (Flousek 1989, Eava et al. 2002, Belskii and Lyakhov 2003). Along a heavy metal air pollution gradient Belskie and Lyakhov (2013) found that Birch forest bird species decreased from 73% in the control region to 59% in the impacted region. Eava et al. (2012) found that bird population densities, species diversity and bird biomass around four non-ferrous smelters responded negatively to copper pollution. However, most of these studies on avian responses to environmental pollution focused mainly on heavy metal pollutants produced by non-ferrous smelters and did not consider other air pollutants that may potentially be harmful to birds such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and/or nitrogen dioxide (NO_2).

Coal fired power stations are major sources of air pollution, emitting environmental pollutants mainly in the form of sulphur dioxide (Shindell and Faluvegi 2010). Coal burning power plants are the largest anthropogenic source of SO_2 (Raheem et al. 2009). Global emissions of SO_2 amount to 70-80 million tonnes per year of which more than 80% of this amount is attributed to fossil fuel combustion (Friend 1973, Raheem et al. 2009). Coal fired power stations are the largest contributor to the energy sector in South Africa. Nearly 70% of the country’s primary energy is generated through coal burning power plants (Winkler 2006). Being the least expensive option for generating power and with the growing demand for electricity, the South African government is embarking on expanding electricity production by constructing more coal fired power stations in the country (e.g. Kusile and Medupi). However, these coal fired power plant expansion initiatives have raised environmental concerns as power stations are the largest contributor to air pollution in South Africa (Winkler 2006).

When coal is burned about 95% of sulphur present in the mineral is released as SO_2 into the atmosphere (Franco and Diaz 2009). In the atmospheric environment SO_2 can either react with water vapour to form sulphuric acid (H_2SO_4) which is released into the biosphere during precipitation as acid rain (wet deposition) or it can settle onto the terrestrial ecosystem in its gaseous state as dry deposition (Treissman et al. 2003). Exposure of plants to high levels of SO_2 can result in acute injury in the form of foliar necrosis (Griffiths 1998). This leads to decreased biomass production and yield reduction in crops (Swain and Padhi 2013). Few studies have documented the effects of SO_2 pollution on bird population densities (Turner 1982, Dulal and Pratap 2011); however, the information available is insufficient to draw conclusions regarding bird community responses to SO_2 exposure.

Matimba is a coal fired power station, owned by Eskom, which has been in operation for over 20 years. Medupi is also an Eskom owned coal fired power station under construction within the precinct of Matimba that is expected to begin its operations in 2015. The current status of birds around these two power stations is not known. Consequently the study area provides the opportunity to investigate bird species response to SO_2 air pollution from coal fired power plants. In this regard the current study seeks to; (1) determine the current influence of SO_2 air pollution on bird population density and species diversity prior to the commencement of operations at Medupi power station (2) determine the environmental variables that affect the bird populations around Matimba power station and (3) establish a baseline against which future studies can assess the influence of SO_2 air pollution on birds once Medupi power station is fully operational. It is hypothesised that SO_2 emitted from Matimba power station does not affect the species diversity and density of birds around the power station.

3.2 Material and Methods

3.2.1 Study area

Matimba and Medupi power stations are situated in the Lephalale local municipality (between 23° 40' - 23° 42' S and 27° 33' - 27° 36' E) within the Waterberg district, Limpopo Province (Figure 1). The climate of Lephalale is semi arid experiencing summer rainfall with dry winters. The annual summer rainfall averages between 250 – 500 mm and mean monthly temperature ranges from 14.6 ^{o}C to 29.1 ^{o}C. The elevation ranges from 750 to 1200 m asl (Lephalale Local Municipality 2014).

The vegetation type for the study area is explained by Mucina and Rutherford (2006) as Limpopo Sweet Bushveld (or Sweet Bushveld) which is a subdivision of the Savanna biome. This vegetation type occurs on plains and low-lying areas dominated by sandy-clayey loams. Sweet Bushveld is described as short, open to closed woodland dominated by shrubs *Dichrostachys cinerea* and *Rhigozum obovatum* as well as taller trees such as *Acacia nigrescens*, *Combretum apiculatum* and *Terminalia sericea*. The herbaceous layer is often coarse dominated by grasses such as *Eragrostis pallens*, *E. trichophora* and *Brachiari nigropedata*. In the present study we selected three sites based on the prevailing wind direction (Table 3–1). In general, north-easterly winds prevail in the area therefore it is expected that SO_2 levels will be highest in a south-westerly direction (KR) from Matimba power station and lowest in a north-easterly direction (ABR and MNR) (Table 3–1, Figure 3-1). Special consideration was taken in site selection so that the sites would have similar habitat types i.e. relatively shrub-dominated open woodlands were characteristic of the study sites. At each site we randomly selected 10 sampling points.

Table 3–1: Study sites and acronyms.

Site	Acronym	Elevation (m)	Latitude (S°)	Longitude (E°)
Kalamahala Range	KR	904	23°48'13.01"	27°25'57.34"
Anglocoal Bulklip Range	ABR	795	23°31'00.98"	27°35'31.13"
Manketti Nature Reserve	MNR	870	23°36'37.70"	27°34'36.75"

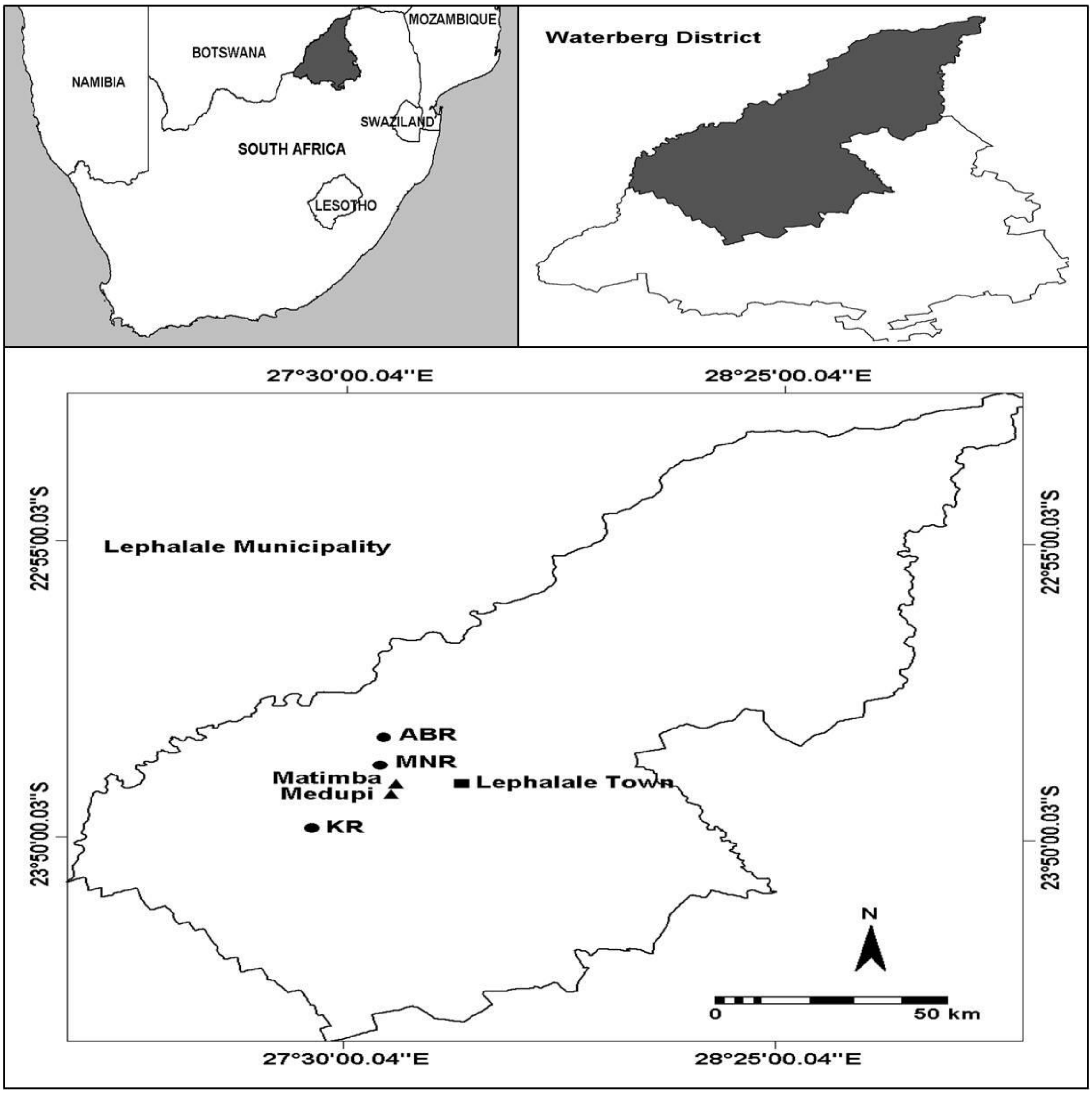


Figure 3-1: Map of the study area.

3.2.2 Bird survey

Bird community data were collected between mid-February and early-March 2014. The sites were visited in the morning between 06:00 and 10:00 when avian activity was expected to be highest, avoiding strong winds and rainy conditions. Birds were counted for 10 min following a 2-minute settling period per point, and all birds detected visually (using binoculars) and audibly within a radius of 50 m from the observer were recorded using single point counts (Bibby et al. 2000). Each site was sampled three times during the breeding period giving a total of 3 point counts per point per site. At each site, the distance between the sampling points was at least 150 m apart, which is a minimum recommended distance for establishing point count stations and avoid double counting of the same bird (Huff et al. 2000). From the avian data relative bird species density and bird species diversity were calculated for each point and were used as dependent variables in the analyses. Relative bird species density (spp./ha) was determined by dividing the total number of bird species recorded per point by the circular plot area of 0.7857 ha. Bird species diversity was calculated using the Simpson (1-D) index as it is considered to have less bias and a lower coefficient of variation compared with other diversity indices (Mouillot and Leprêtre 1999).

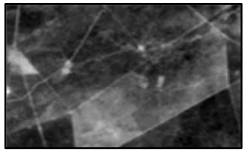
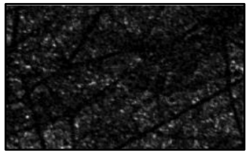
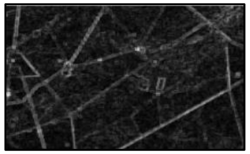
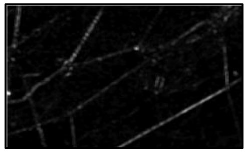
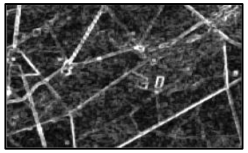
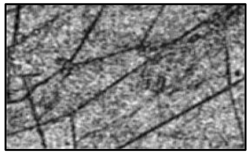
3.2.3 Remote Sensing and Image texture analysis

MacArthur and MacArthur (1961) hypothesized that biodiversity is controlled by three main factors: productivity, habitat structure and climate stability. In this study, focus was on the first two factors (productivity and habitat structure) and terrain as a physical factor which may influence avian biodiversity. Productivity is the quantity of energy available to organisms within a system (Parviainen et al. 2010). It has a major influence on avian biodiversity, especially bird species richness (Seto et al. 2004, St-Louis et al. 2009). Remote sensing indices, specifically Normalised Difference Vegetation Index (NDVI) can provide direct estimates of primary productivity as it measures the energy entering the ecosystem (Tucker and Sellers 1986, Paruelo et al. 1997). NDVI varies temporally and has been used extensively to monitor the seasonal changes in vegetation at large spatial scales (Hill and Donald 2003). In order to characterize productivity within the study area, cloud free Landsat 8 OLI (Operational Land Imager) imagery (30 m x 30 m) was acquired on 7 January 2014. The image was captured during the growing season so that it corresponded with the avian breeding period in the study area. NDVI for the study area was generated in a GIS environment using the Near Infrared and Red bands. At each point location within the three sites, the mean and standard deviation values of a square of 3 x 3 pixels (90 m x 90 m area) were extracted from the NDVI image, which matched the circular plot area of each point count. Mean NDVI (primary productivity) and standard deviation of NDVI (vegetation heterogeneity) values were used for the analyses as previous work has established them to be effective substitute measures of primary productivity and vegetation heterogeneity respectively (Seto et al. 2004).

Habitat structure can be defined as the vertical and horizontal configuration or arrangement of vegetation within a habitat (Culbert et al. 2012). At fine scales habitat structure is strongly associated with bird assemblages (Bersier and Meyer 1994). A greater variety in habitat structure leads to a greater diversity in bird species (Tews et al. 2004). Remote sensing imagery can characterize habitat structure through image texture measures. Image texture is defined as the variation in pixel reflectance values within an image or an area within an image (Haralick et al. 1973, Carr 1999). Texture measures can capture variations within and between habitat structures (Culbert et al. 2012). Texture measures are divided into two groups: first-order (occurrence) measures and second-order (co-occurrence) measures. First-order measures are summary statistics used to capture pixel value properties while second-order measures are derived from grey-level co-occurrence matrix (GLCM) (Haralick et al. 1973). Second order measures take into account the spatial arrangement and dependencies of pixel values (Coburn and Roberts 2004). Band 5 (Near Infrared) of the Landsat 8 scene was used to calculate image texture measures as infra red light is strongly reflected by green vegetation (Gausman 1977). Three first-order texture measures (mean, range and standard deviation) and four second-order texture measures (angular second moment, contrast, correlation and homogeneity) were used as these measures were previously shown to be useful in characterizing habitat structure (Kuplich et al. 2005, Lu and Batistella 2005, Dobrowski et al. 2008) and the four second-order texture measures used are least correlated with each other as compared to other second-order texture measures (Baraldi and Parmiggiani 1995). These texture variables were calculated from the spectral values for the near infra red band imagery using a defined neighbourhood (moving window). A 3 x 3 moving window size was used for both image texture measures (first-order and second-order) as it can capture heterogeneity of pixel values over small areas (Wood et al. 2012). The mean and standard deviation values for each sample point were extracted for each texture measure.

Terrain analysis was also conducted using an ASTER GDEM2 (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 2) with a pixel resolution of 1 arc-second (≈30 m), obtained from NASA Global Data Explorer (http://gdex.cr.usgs.gov/gdex/, accessed 2014). Two elevation variables were calculated from the DEM for each sample point: coefficient of variation and mean elevation, and were used as independent variables in the analyses.

Table 3–2: Image texture description and formula (adapted from Haralick et al. 1973).

First-order measures				Second-order measures			
Texture Measure	Statistical description	Formula	Example (3 x 3 window)	Texture Measure	Statistical description	Formula	Example (3 x 3 window)
Mean	Average pixel value within a defined neighbourhood	$\frac{\sum x}{n}$		Angular Second Moment	A measure of how regular or orderly the pixel values are across an image	$\sum_i \sum_j \{p(i,j)\}^2$	
Range	A measure of the difference between the maximum and minimum pixel values within a defined neighbourhood	$\max\{X\} - \min\{X\}$		Contrast	A measure of the amount of local variation in pixel values within an image	$\sum_i \sum_j p_{ij^{(i-j)^2}}$	
Standard deviation	A measure of variability of pixels within a define neighbourhood	$\sqrt{\frac{\sum(x-\bar{x})^2}{n}}$		Correlation	It is the measure of the linear dependency in pixel values among neighbouring pixels	$\frac{\sum_i \sum_j (ij) p_{ij} - \mu_x \mu_y}{\sigma_x \sigma_y}$	
				Homogeneity	A measure of homogenous pixel values across an image	$\sum_i \sum_j \frac{1}{1+(i-j)^2} p(i,j)$	

3.2.4 SO_2 modeling

AERMOD is a steady-state plume dispersion model (Perry et al. 2004). It simulates the dispersion of pollutants over a short range (up to 50 km). The forecasts are based on boundary layer turbulent structure and scaling concepts (Zou 2010). The model presumes that concentrations at all distances during a modeled hour are influenced by a set of hourly meteorological inputs which are held constant (Touma et al. 2007). It was developed by the American Meteorological Society (AMS) and the United States Environmental Protection Agency (EPA) as an advancement of the ISCT3 (Industrial Source Complex Short-Term 3) pollution dispersion model. The model's advantage is that it provides a dynamic treatment of the vertical structure of the planetary boundary layer (Perry et al. 2004). The AERMOD modeling system consists of two pre-processors AERMAP (AERMOD terrain pre-processor) and AERMET (AERMOD meteorological pre-processor). AERMET uses meteorological data (cloud cover, temperature, wind speed and direction) to generate planetary boundary layer parameters. AERMAP is used to calculate terrain and critical hill height values for each receptor location within the user defined model domain (Touma et al. 2007). AERMOD was used to compute SO_2 concentrations in the ambient air surrounding Matimba power station for the period January 2011 to December 2013. Annual average SO_2 concentration, average monthly SO_2 concentration and 1-hour average SO_2 concentrations were calculated using the model. The SO_2 concentration values from the model output were extracted for each sample point and analysed together with the bird data. AERMOD was also used to predict the SO_2 concentration in the ambient air surrounding both Matimba and Medupi power station. The SO_2 concentration output maps were classified into three concentration classes: low, medium and high. Defining these classes was done subjectively, based on previous literature related to birds and SO_2 air pollution.

3.2.5 Statistical analysis

Changes in bird population densities and bird diversity are not defined in most cases by a single factor but are the outcome of multiple contributing factors (Diamond 1988, Temple 1988). The relationship between the observed bird species density/diversity and the environmental variables were investigated by applying a series of simple regression models. Correlation analysis was used to test the hypothesis that ambient SO_2 pollution from Matimba power station influences bird population density changes in the Lephalale area. Pearson's product moment correlation was used for the analysis as the bird data was found to be normally distributed. The relationship between bird species density and SO_2 polluted air was further explored by looking at specific species responses at the sample sites. In the event that SO_2 concentration variables and environmental variables (productivity, habitat structure and elevation) both exhibit significant correlations with the observed bird species density and diversity, multiple regression analysis was applied. The purpose of multiple regression analysis is not to make a strict separation between the effects of ambient SO_2 and environmental influences but rather to determine which variable(s) contribute most to the observed variation in avian biodiversity around the power stations.

3.3 Results

3.3.1 Variation in bird species richness

During the bird surveys a total of 1 400 individual birds and 70 species were observed (see Appendix A). The total number of birds and species recorded during the study is shown in Table 3–3. There was a significant variation in bird species richness (one-way ANOVA, $F_{2,27} = 6.075$, $p = 0.01$) between the three sample sites. Bird species richness and abundance increased from the least in Kalamhala Range, to the most at Manketti Nature Reserve. Forty one percent of the birds recorded were found in Manketti Nature Reserve with Anglocoal Bulklip Range and Kalamahala Range contributing 34% and 25% of the observed birds respectively.

Table 3–3: Species recorded at the three study sites.

Site	Bird abundance (individuals)	Species richness (species)
Kalamahala range	353	42
Anglocoal Bulklip range	479	47
Manketti nature reserve	568	54

Rarefaction curves (Figure 3-2) showing sampling at the three sites showed that all three curves started reaching an asymptote, indicating that most of the bird species present at these sample sites had been recorded. Consequently, comparisons of bird species richness and diversity can be made between the three sites.

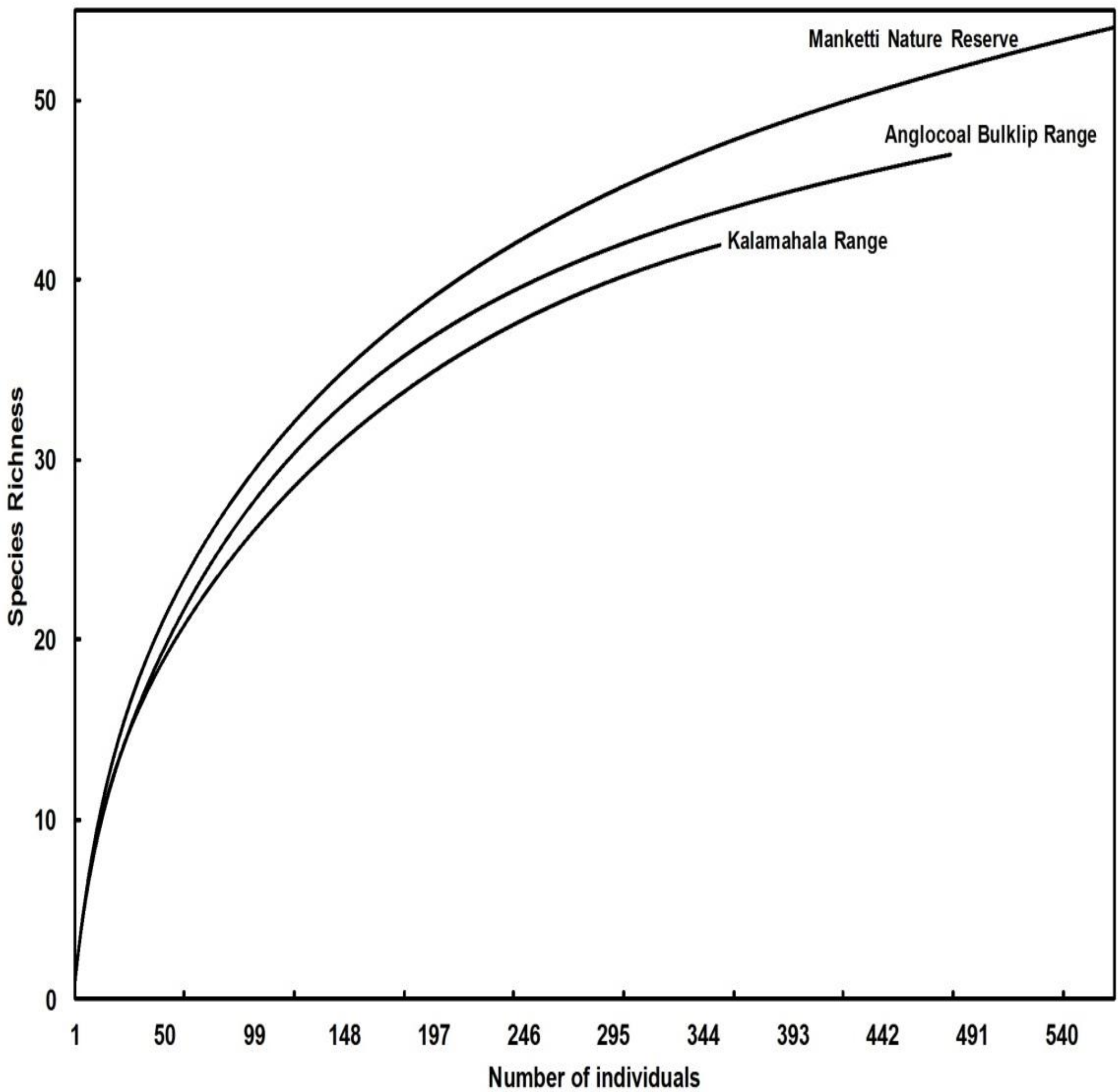


Figure 3-2: Individual-based rarefaction curves for the three sample sites.

3.3.2 Variation in bird species density and diversity

Our bird species density (Shapiro-Wilks, W = 0.943, p = 0.11) and bird diversity (Shapiro-Wilks, W = 0.957, p = 0.26) data had a Gaussian distribution. A clear trend can be observed from the box plots (Figures 3-3 and 3-4), bird species density and diversity were greater in a north-easterly direction from Matimba and Medupi power stations (Anglocoal Bulklip Range and Manketti Nature Reserve) as compared with the south-westerly direction (Kalamahala Range). There was a significant variation in bird species density (one-way ANOVA, $F_{2,27}$ = 7.876, p = 0.002) between the three sample sites. Multiple comparisons (Tukey's) of bird species density between the three sample sites revealed that bird species density at Kalamahala Range (M = 44.93, p = 0.001) was significantly lower compared to that at Manketti Nature Reserve (M = 72.29). There were no statistically significant differences between bird species density at Anglocoal Bulklip Range (M =

60.96) compared with Manketti Nature Reserve (p = 0.25) and Kalamahala Range bird species density compared to that at Anglocoal Bulklip Range (p = 0.07).

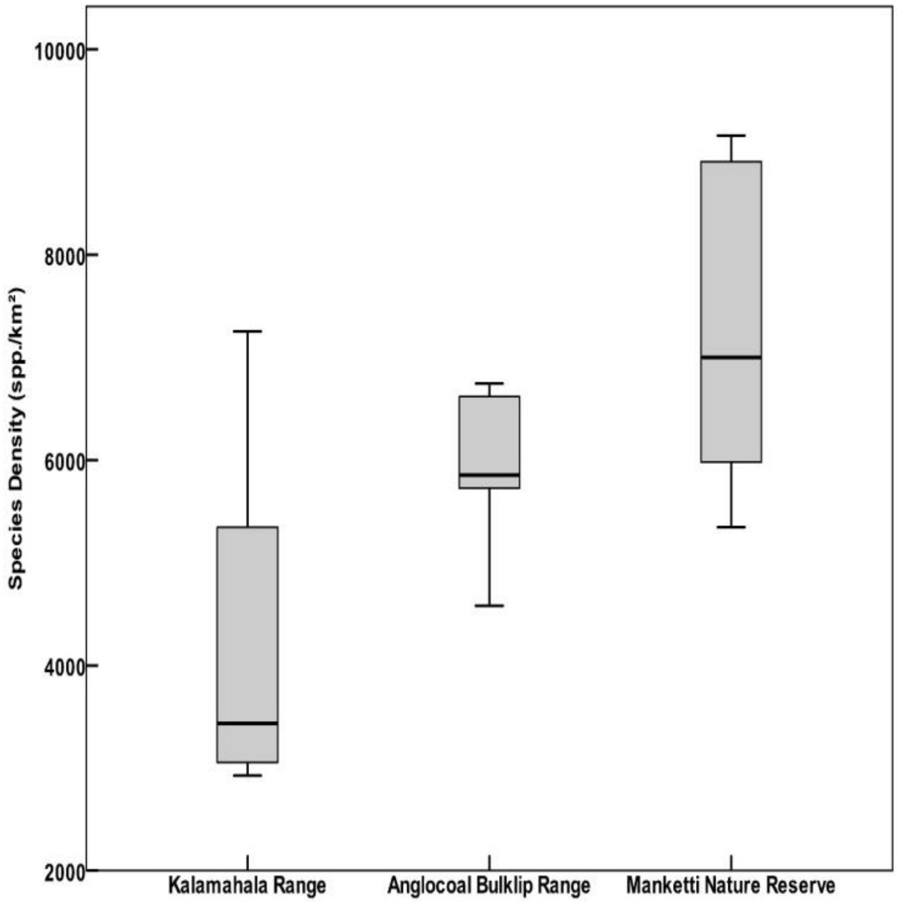


Figure 3-3: Comparison in mean bird species density between the three sample sites.

Bird diversity varied (one-way ANOVA, $F_{2,27}$ = 4.506, p = 0.02) between the three sample sites. Multiple comparisons (Tukey's) of bird diversity between the three sample sites showed that bird diversity at Anglocoal Bulklip Range (M = 0.920, p = 0.03) was considerably higher to that at Kalamahala Range (M = 0.897). However, there were no statistically significant differences between the bird diversity at Anglocoal Bulklip range and Manketti Nature Reserve (p = 0.95), and between Kalamahala Range bird diversity to that at Manketti Nature Reserve (p = 0.06).

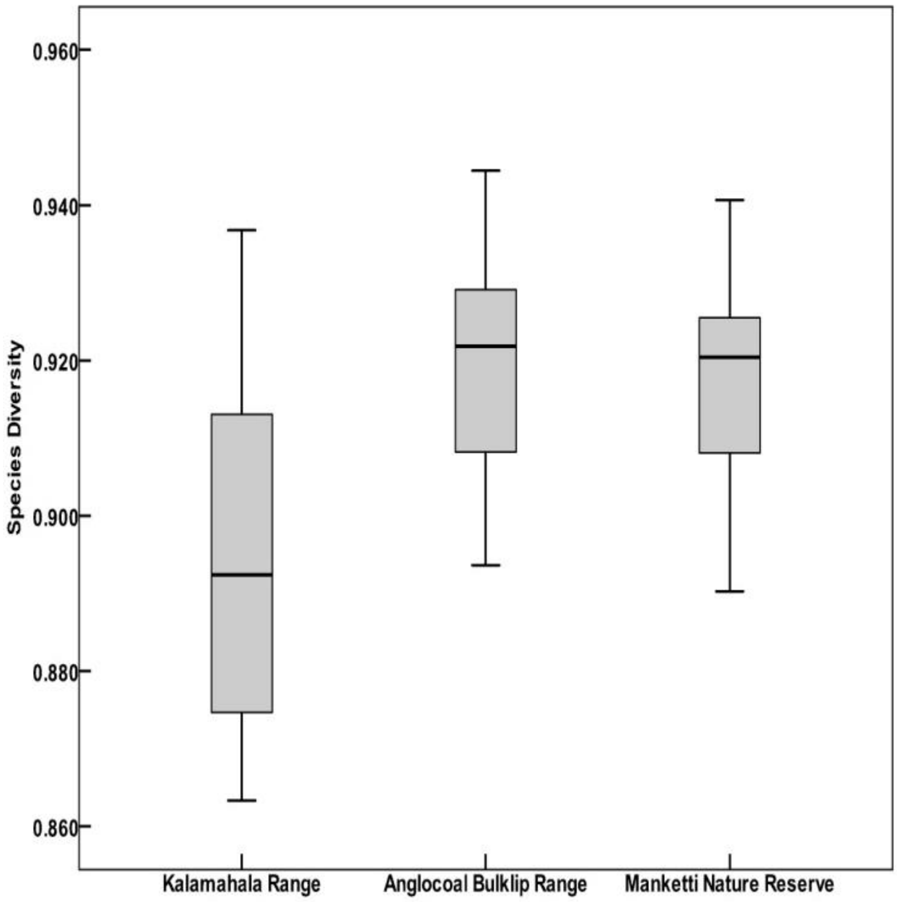


Figure 3-4: Comparison in mean bird diversity between the three sample sites.

3.3.3 Relationships between bird species density and environmental variables

Bird species density at Anglocoal Bulklip Range showed a significant ($R^2 = 0.75$, $p < 0.01$) positive relationship with the standard deviation of NDVI (Table 3–4). No relationship between bird species density and environmental variables were found at Kalamahala Range ($p > 0.05$) nor Manketti Nature Reserve ($p > 0.05$). Supplementary data of scatter plots showing the relationships between bird species density and environmental variables is given in Appendix B.

3.3.4 Relationships between bird diversity and environmental variables

Fifty percent of the variation in bird diversity at Anglocoal Bulklip range was associated with mean NDVI ($p = 0.02$, Table 3–5). There was a significant ($R^2 = 0.66$, $p < 0.01$) negative association between second order homogeneity and species diversity at Kalamahala Range. Bird diversity at Manketti Nature Reserve was not ($p > 0.05$) associated with any of the environmental variables. Supplementary data of scatter plots showing the relationships between bird diversity and environmental variables is given in Appendix C.

Table 3–4: Results of linear regressions between bird species density and environmental variables.

	Kalamahala Range (n = 10)			Anglocoal Bulklip Range (n = 10)			Manketti Nature Reserve (n = 10)		
	Model	R^2	*P*	Model	R^2	*P*	Model	R^2	*p*
<u>Primary productivity</u>									
NDVI Mean	y = 6083.6x + 4767.1	0.002	0.90	y = 7204.1x + 6445.8	0.01	0.83	y = -50527x + 5288.9	0.09	0.41
NDVI SD	y = -61807x + 5243.7	0.12	0.32	y = 139905x + 4953.3	**0.75**	**<0.01**	y = -107968x + 8302.3	0.07	0.46
<u>Habitat structure</u>									
Mea n_3 x 3_Mean	y = 122104x - 25729	0.39	0.053	y = 26861x - 523.35	0.08	0.43	y = -43473x + 18154	0.17	0.24
Mean_3 x 3_SD	y = -78975x + 5003.7	0.02	0.67	y = 137510x + 5536.7	0.05	0.55	y = -461009x + 8303.2	0.13	0.12
Range_3 x 3_Mean	y = 23890x + 3673.3	0.02	0.68	y = 55476x + 4182.4	**0.67**	**<0.01**	y = 7092x + 6962.4	0.001	0.93
Range_3 x 3_SD	y = 259681x + 1812.8	0.35	0.07	y = 81755x + 5260.8	**0.62**	**0.01**	y = -232468x + 8607.6	0.33	0.08
SD_3 x 3_Mean	y = 42162x + 3999.4	0.01	0.78	y = 157958x + 4279.9	**0.59**	**0.01**	y = 109770x + 5813.1	0.04	0.57
SD_3 x 3_SD	y = 759578x + 1970.9	0.35	0.07	y = 265264x + 5221	**0.60**	**0.01**	y = -461009x + 8303.2	0.13	0.31
ASM_3 x 3_Mean	y = 10687x + 2713.3	0.02	0.71	y = -21162x + 9310.8	0.45	0.04	y = 9931.5x + 5749.3	0.06	0.50
ASM_3 x 3_SD	y = 30503x + 3226.2	0.08	0.41	y = -33534x + 7096.3	0.20	0.19	y = 13312x + 6844.6	0.08	0.44
Contrast_3 x 3_Mean	y = 14.195x + 4401	0.001	0.93	y = 105.88x + 5213.6	**0.68**	**<0.01**	y = 134.31x + 6113.5	0.19	0.20

Contrast_3 x 3_SD	y = 702.38x + 2835.2	0.17	0.23	y = 286.79x + 5319.5	**0.51**	**0.02**	y = 193.27x + 6585.9	0.11	0.35
Correlation_3 x 3_Mean	y = 1.9646x + 4831	0.04	0.60	y = 0.5986x + 6304.4	0.06	0.49	y = -0.5187x + 7106.6	0.01	0.75
Correlation_3 x 3_SD	y = -0.9062x + 4791.9	0.04	0.60	y = -0.5845x + 6474.9	0.25	0.15	y = 0.3346x + 7134.1	0.01	0.79
Homogeneity_3 x 3_Mean	y = 1919x + 3722.6	0.01	0.79	y = -4693.4x + 7791.2	**0.47**	**0.03**	y = -4393.6x + 8861.7	0.14	0.28
Homogeneity_3 x 3_SD	y = 33246x + 1620.6	0.10	0.37	y = -5050.9x + 6520.5	0.01	0.74	y = 12941x + 5744.4	0.15	0.26
Terrain analysis									
Elevation Mean	y = -17.934x + 20655	0.004	0.86	y = 11.54x - 3196.6	0.02	0.71	y = -28.859x + 32229	0.07	0.45
Elevation Coefficient of variation	y = 101600x + 4127	0.01	0.82	y = -35021x + 6302.3	0.01	0.83	y = 36034x + 7028.4	0.01	0.75

Table 3–5: Results of linear regressions between species diversity and environmental variables.

	Kalamahala Range (*n* = 10)			Anglocoal Bulklip Range (*n* = 10)			Manketti Nature Reserve (*n* = 10)		
	Model	R^2	*p*	Model	R^2	*p*	Model	R^2	*p*
Primary productivity									
NDVI Mean	y = -0.8906x + 0.8564	0.35	0.07	y = 1.1322x + 0.9749	**0.50**	**0.02**	y = 0.6034x + 0.9405	0.10	0.37
NDVI SD	y = 0.6448x + 0.8887	0.10	0.38	y = -0.2769x + 0.9223	0.01	0.78	y = 1.288x + 0.9045	0.08	0.42
Habitat structure									
Mea n_3 x 3_Mean	y = -0.9322x + 1.1272	0.16	0.25	y = 0.7097x + 0.7451	0.19	0.21	y = 0.097x + 0.893	0.01	0.82
Mean_3 x 3_SD	y = 1.2743x + 0.8883	0.05	0.56	y = 4.3087x + 0.9025	0.16	0.26	y = 0.2206x + 0.9161	0.001	0.93
Range_3 x 3_Mean	y = 0.1143x + 0.8926	0.004	0.87	y = 0.0365x + 0.9187	0.001	0.93	y = 0.5151x + 0.898	0.05	0.53
Range_3 x 3_SD	y = -0.0352x + 0.8969	0.0001	0.99	y = -0.3718x + 0.9238	0.04	0.56	y = -0.1879x + 0.9184	0.002	0.91
SD_3 x 3_Mean	y = -0.0449x + 0.897	0.0001	0.98	y = 0.0574x + 0.9193	0.0003	0.96	y = 0.0515x + 0.9167	0.0001	0.98
SD_3 x 3_SD	y = -3.6416x + 0.9086	0.06	0.50	y = -1.7107x + 0.9256	0.09	0.41	y = 1.5123x + 0.9138	0.01	0.77
ASM_3 x 3_Mean	y = 0.0776x + 0.8836	0.007	0.82	y = -0.1782x + 0.9471	0.11	0.35	y = -0.0656x + 0.9271	0.02	0.69
ASM_3 x 3_SD	y = 0.5302x + 0.8745	0.18	0.22	y = -0.0371x + 0.9211	0.001	0.94	y = -0.0353x + 0.9183	0.005	0.86
Contrast_3 x 3_Mean	y = -0.0007x + 0.9007	0.02	0.73	y = -0.0004x + 0.9236	0.04	0.58	y = 0.0011x + 0.9082	0.11	0.36

Contrast_3 x 3_SD	y = -0.006x + 0.9106	0.25	0.40	y = -0.0022x + 0.926	0.11	0.36	y = 0.0025x + 0.9089	0.16	0.26
Correlation_3 x 3_Mean	y = -6E-05x + 0.8869	0.21	0.18	y = 5E-07x + 0.9202	0.0001	0.98	y = -8E-06x + 0.9155	0.02	0.67
Correlation_3 x 3_SD	y = 3E-05x + 0.8859	0.32	0.09	y = -5E-06x + 0.9232	0.06	0.49	y = 3E-06x + 0.9164	0.01	0.81
Homogeneity_3 x 3_Mean	y = -0.0227x + 0.9056	0.01	0.79	y = -0.0258x + 0.9293	0.05	0.54	y = -0.0198x + 0.9247	0.02	0.67
Homogeneity_3 x 3_SD	y = -0.9983x + 0.9828	**0.66**	**<0.01**	y = -0.3003x + 0.9452	0.17	0.23	y = -0.061x + 0.9243	0.03	0.64
Terrain analysis									
Elevation Mean	y = -2E-05x + 0.9172	0.0001	0.98	y = 0.0006x + 0.397	0.20	0.19	y = -0.0001x + 1.0104	0.01	0.80
Elevation Coefficient of variation	y = -1.6632x + 0.9025	0.01	0.75	y = -2.3885x + 0.934	0.10	0.36	y = -1.3078x + 0.9246	0.15	0.28

3.3.5 Modelled ambient SO_2 concentrations

Modelled hourly average concentrations for Matimba in Figure 3-5 showed that pollutant plumes of high SO_2 concentration were found within close proximity to the power stations and these pollutant plumes were expected to expand in the north-westerly, north-easterly (into Anglocoal Bulklip Range) and south-westerly (into Kalamahala Range) direction once operations at Medupi power station have commenced (Figure 3-5).

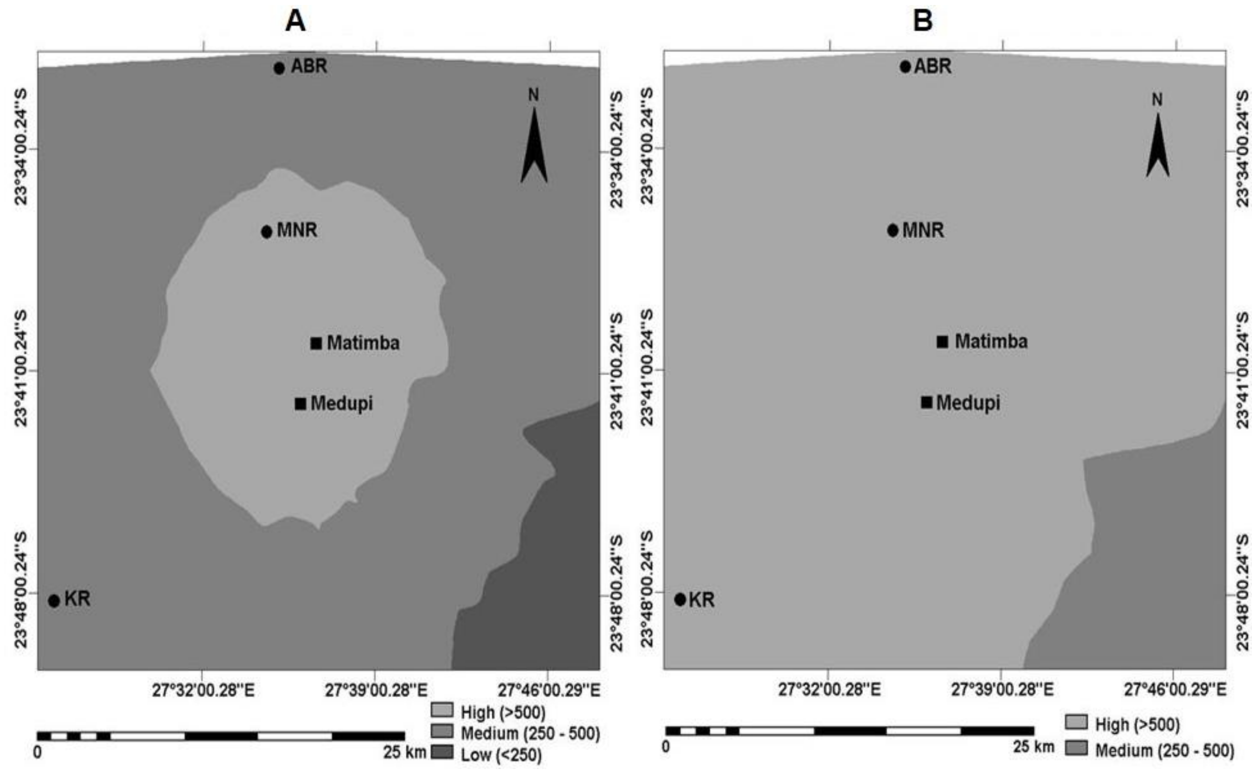


Figure 3-5: SO_2 1-hour average concentrations (µg/m^3) for A) Matimba, and for B) Matimba combined with Medupi.

Simulated monthly average concentrations for Matimba (Figure 3-6) showed SO_2 pollutant plumes moving in a south-westerly direction with the highest concentration values recorded in close proximity to Medupi power station. Predicted combined monthly average concentrations for Matimba and Medupi power station revealed that the pollutant plumes with high SO_2 concentration were likely to expand in the south-westerly direction encroaching into Kalamahala Range as shown in Figure 3-6. Pollutant plumes with moderate SO_2 levels were predicted to expand in the south-easterly, north-easterly (into Anglocoal Bulklip Range) and north-westerly direction.

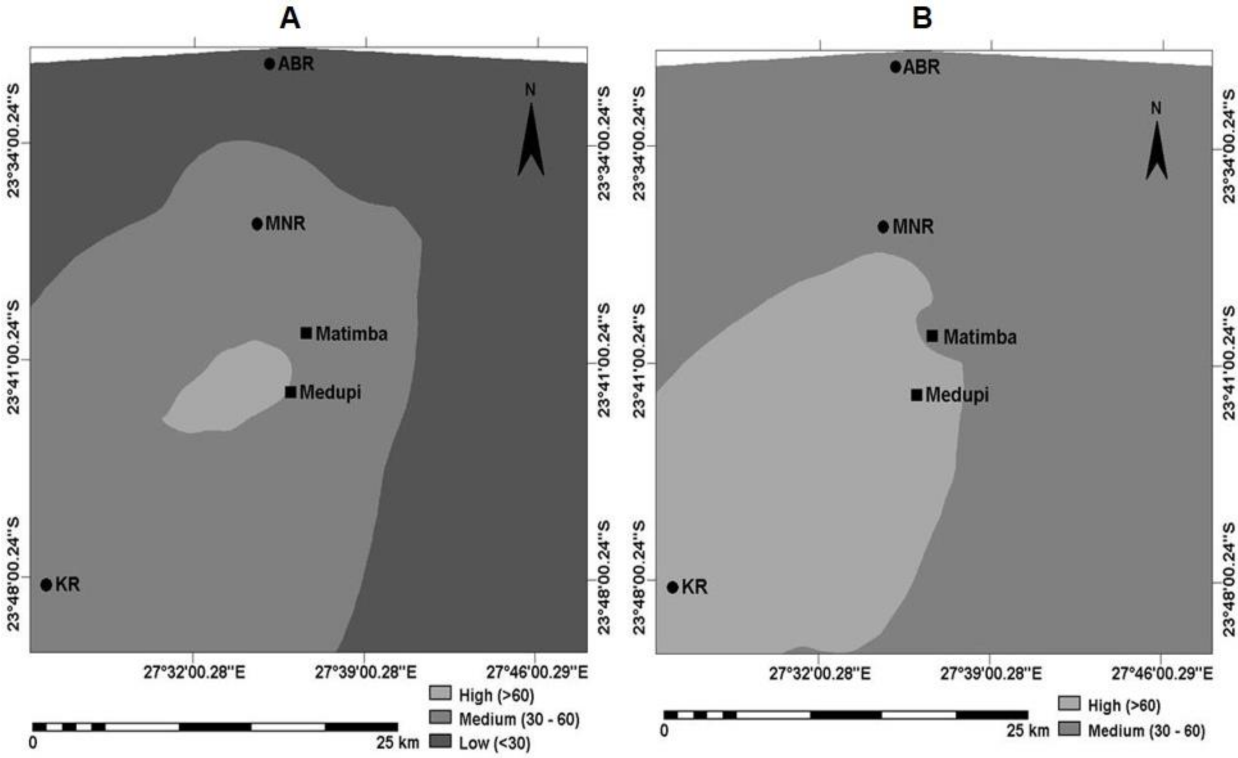


Figure 3-6: SO_2 monthly average concentrations (µg/m^3) for A) Matimba, and for B) Matimba combined with Medupi.

Modelled annual average concentrations for Matimba (Figure 3-7) show SO_2 pollutant plumes moving in a south-westerly direction with the highest concentration values recorded in close proximity to Medupi power station. Once operations at Mepudi power station have commenced pollutant plumes with high SO_2 concentration are expected to expand in the south-westerly direction encroaching Kalamahala Range as shown in Figure 3-7. Pollutant plumes with moderate levels of SO_2 are predicted to expand in the south-easterly, north-easterly (into Anglocoal Bulklip Range) and north-westerly direction.

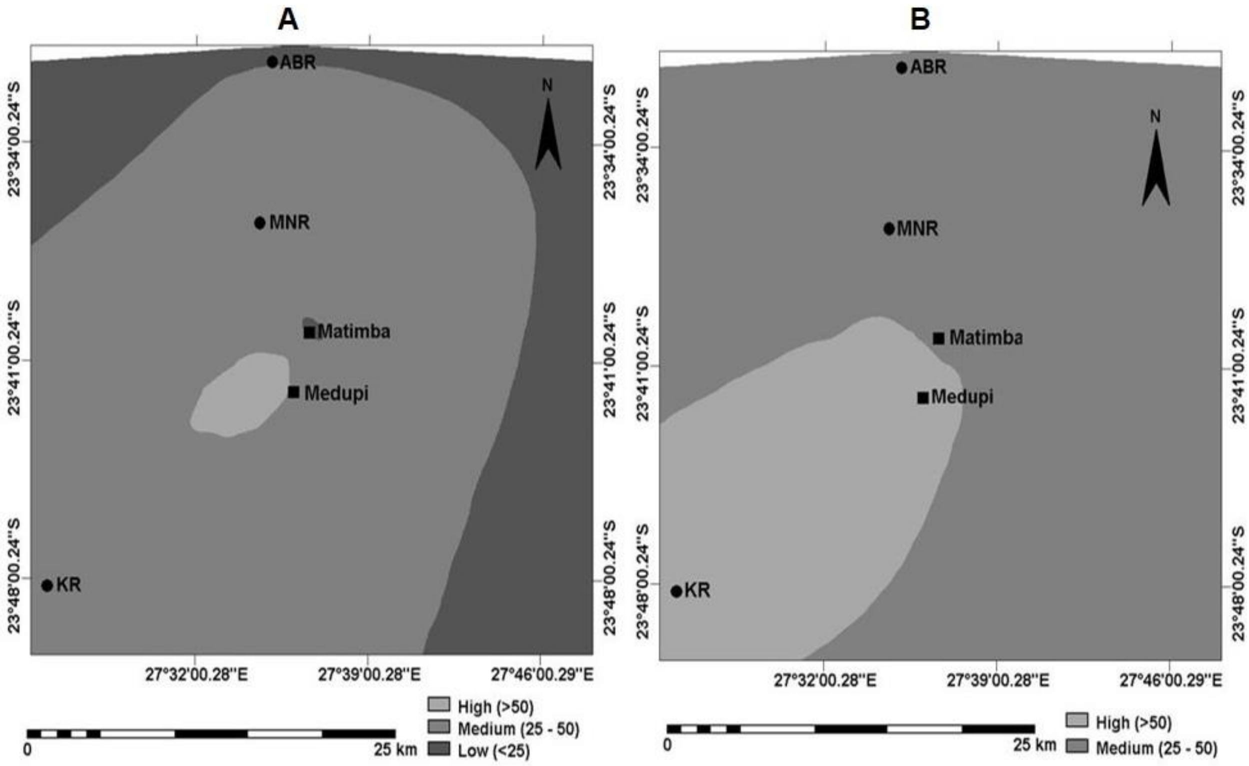


Figure 3-7: SO_2 annual average concentrations (µg/m^3) for A) Matimba, and for B) Matimba combined with Medupi.

3.3.6 Bird species density associations with SO_2 concentrations

There is currently no correlation between bird species density and hourly, monthly and annual mean SO_2 concentrations at Kalamahala Range ($R = 0.41$, $R = 0.34$, $R = 0.35$ and $p = 0.24$, $p = 0.33$, $p = 0.32$ respectively), Anglocoal Bulklip Range ($R = 0.37$, $R = -0.35$, $R = -0.37$ and $p = 0.29$, $p = 0.33$, $p = 0.29$) and Manketti Nature Reserve ($R = 0.53$, $R = 0.60$, $R = 0.50$ and $p = 0.11$, $p = 0.07$, $p = 0.14$). Therefore we reject the hypothesis that SO_2 air pollution from Matimba power station influences bird population density changes in the Lephalale area.

Multiple linear regression revealed that vegetation heterogeneity (standard deviation of NDVI) and habitat structure (2nd order homogeneity) were significantly related to bird species density at Anglocoal Bulklip Range with the model ($F_{1,6} = 14.976$, $p = 0.008$) accounting for 95% of the variance in bird species density (Adjusted $R^2 = 0.95$). Habitat structure, vegetation productivity, SO_2 concentration and elevation at both Kalamahala Range and Manketti Nature Reserve were not associated ($p > 0.05$) with changes in the density of bird species at these two sample sites.

3.3.7 Bird diversity associations with SO_2 concentrations

There is no significant relationship between bird diversity and hourly, monthly and annual mean SO_2 concentrations at Kalamahala Range (R = -0.17, R = -0.09, R = -0.13 and p = 0.65, p = 0.80, p = 0.72 respectively), Anglocoal Bulklip Range (R = 0.17, R = -0.17, R = -0.09 and p = 0.65, p = 0.64, p = 0.81) and Manketti Nature Reserve (R = -0.08, R = -0.04, R = -0.11 and p = 0.82, p = 0.91, p = 0.77).

Multiple linear regression for Anglocoal Bulklip Range revealed that primary productivity (mean NDVI) and habitat structure (2nd order homogeneity) were significantly related to bird diversity with the model ($F_{1,7}$ = 18.147, p = 0.004) accounting for 82% of the variance in bird diversity (Adjusted R^2 = 0.82). At Kalamahala Range, habitat structure (2nd order homogeneity) and elevation (coefficient of variation) were significantly related to bird diversity with the model ($F_{1,7}$ = 13.669, p = 0.008) accounting for 85% of the variation in bird diversity (Adjusted R^2 = 0.85). No significant (p > 0.05) model was produced for Manketti Nature Reserve suggesting that the measured variables did not influence changes in the diversity of birds at this sample site.

3.4 Specific species responses

Of the species at the three sites for which we could calculate the density estimates and statistically test, only two species exhibited some measure of response to SO_2 air pollution around Matimba power station. At Anglocoal Bulklip Range, the density of *Batis molitor* (Chinspot Batis) was negatively correlated with the monthly (R = -0.68, p = 0.03) and annual (R = -0.69, p = 0.03) average SO_2 concentrations. However, for hourly average concentrations (Figure 6) *Batis molitor* density exhibited a positive correlation (R = 0.68, p = 0.03).

Streptopelia senegalensis density at Kalamahala range was negatively correlated (R = -0.644, p = 0.04) with the monthly average SO_2 concentrations. There were no correlations between *Streptopelia senegalensis* density and hourly and annual average SO_2 concentrations (R = -0.58, p = 0.08 and R = -0.61, p = 0.06).

Multiple linear regression revealed that habitat structure (1st order mean) is the best predictor ($F_{1,8}$ = 10.271, p = 0.01) accounting for 51% of the variation in *Batis molitor* density (Adjusted R^2 = 0.51) at Anglocoal Bulklip Range. At Kalamahala Range, habitat structure (1st order Range) was significantly related to the density of *Streptopelia senegalensis* with the model ($F_{1,8}$ = 7.495, p = 0.03) accounting for 42% of the variation in *Streptopelia senegalensis* density (Adjusted R^2 = 0.42).

3.5 Discussion

This study explored the possible effects of SO_2 pollution on avian biodiversity. Currently, SO_2 polluted air seems not to have any effects on the diversity and density of breeding birds around Matimba power station. However this situation may change when operations at Medupi have commenced as the combined emissions from both Matimba and Medupi will likely increase the SO_2 concentration levels around Lephalale. From our results we observed that variation in bird species density at Anglocoal Bulklip Range and variation in bird diversity at both Kalamahala Range and Anglocoal Bulklip Range are best explained by habitat structure and vegetation productivity. These results corroborate MacArthur and MacArthur's (1961) hypothesis which states that changes in avian biodiversity are mainly influenced by habitat structure, productivity and climate stability. Through multiple regression analysis we identified parsimonious models that were in general agreement with the observed bird species density and diversity data. However making a strict separation between natural effects (MacArthur and MacArthur 1961) on bird populations from human-induced (e.g. SO_2) changes still remains a challenge as multiple regression analysis can only establish relationships between the dependent variables (bird species density and diversity) and independent variables (habitat structure, vegetation productivity, SO_2 concentration and elevation), but can never be certain about the underlying causal mechanism(s).

Our initial analysis on individual species showed significant relationships between SO_2 air pollution and the densities of the Chinspot Batis and Laughing Dove. These species exhibited some response to SO_2 exposure. However after further investigation using multiple regression analysis it was revealed that variations in the densities of Chinspot Batis and Laughing Dove are best explained by habitat structure. The concentration of SO_2 is currently not high enough to effect significant changes in the densities of these two species. These results are in agreement with an earlier study by Turner (1982) in which the effects of moderate SO_2 pollution on Common House Martin (*Delichon urbicum*), Common Swift (*Apus apus*) and Barn Swallow (*Hirundo rustica*) densities were revealed to be less significant than the influence of the type of habitat available. The Laughing Dove responds more towards land-use changes and habitat disturbance with a high abundance of the Laughing Dove being found on disturbed sites as it has a wide home range (Hockey et al. 2005). The Chinspot Batis had a positive correlation with hourly average SO_2 concentrations but exhibited negative correlations with both monthly and annual average SO_2 concentrations suggesting that the Chinspot Batis may respond more to SO_2 exposure over longer periods than exposure over short periods of time.

Although Chinspot Batis and Laughing Dove both exhibited some measure of response to SO_2 exposure, our results, however, are based on a single season which is not adequate enough to draw conclusions on bird species sensitivity towards SO_2 pollution. Continued monitoring of bird population densities at our study area is required as this will facilitate in the selection of sensitive and relevant species for future ecological impact studies at other coal-fired power stations. Furthermore, although habitat structure has a greater effect on the densities of the Chinspot Batis and Laughing Dove than SO_2 has, it is inconclusive to state that this will remain the same once Medupi power station is operating. Therefore continued monitoring giving particular attention to the two species (i.e. Chinspot Batis and Laughing Dove) is necessary so as to determine if the conditions at both Kalamahala Range and Anglocoal Bulklip Range will remain the same.

Bird species density varied significantly among the study sites but was not related to the distance to the source of the SO_2 air pollution. The general expectation is that bird species density would tend to be lower close to the power plant where SO_2 concentrations are high as opposed to further away from the power plant where SO_2 concentrations are lower and bird species density is higher. However this is not the case as Manketti Nature Reserve which is 7 km away from Matimba power station had a significantly higher bird species density compared to Kalamahala Range which is 23 km away. These results further confirm that SO_2 pollution currently has minimal or no influence on the density and diversity of birds around Matimba power station.

Eskom has been at the forefront of air quality monitoring around Matimba since the inception of the power station. Monitoring began in 1984 before operations commenced at the power station and continued monitoring confirmed that the power station had increased the level of ambient SO_2 in Lephalale (Rorich, 2004). Results from Eskom's monitoring stations in Grootstryd (2005-2006) and Marapong (2007-2010) reveal that SO_2 concentration levels within the proximity of Matimba power station are generally below national ambient air quality standards (Muthige 2013). Although emissions recorded at these stations are low there are some cases when they are high and this could affect specific bird species.

Overall, our results indicate that SO_2 concentration levels surrounding Matimba power station does not have an influence on bird species densities at population level but rather its influence is more species-specific. Heavy metal pollution studies (.i.e. Eava et al. 2002, Eava et al. 2012, Belskii and Belskaya 2013) on bird species densities suggest that responses to heavy metal pollution are species-specific and this could be a similar case too in terms of bird species responses to SO_2 pollution. Due to time, financial constraints and inaccessibility to certain sample sites only three sample sites were investigated. This was a major limitation to our study as there were less data for statistical analysis and conclusions based on a small number of sample sites are less reliable. However this problem can be resolved by incorporating more sample sites in future studies and integrating the results of these studies with our study through meta-analysis.

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CHAPTER 4 CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

4.1 Conclusion

This study explored the relationship between bird species density/diversity and sulphur dioxide (SO_2) concentration levels with the aim of establishing a baseline against which future studies can then assess the influence of SO_2 air pollution on birds once Medupi power station is commissioned. The success of this study will be assessed according to the extent that the objectives set in Chapter 1 were accomplished.

4.1.1 Determine the density and diversity of birds around Matimba and Medupi power station

Using bird point counts we were successfully able to determine the density and diversity of birds around Matimba and Medupi power station. Our findings revealed that bird species density and diversity were greater in the north-easterly direction from Matimba and Medupi power stations (Anglocoal Bulklip Range and Manketti Nature Reserve) as compared to the south-westerly direction (Kalamahala Range). However, there were no significant spatial trends between bird species density/diversity and distance to Matimba power station. Despite being the closest site to Matimba power station, Manketti Nature Reserve had the highest bird species density and richness while Kalamahala Range which was the furthest site away had the lowest bird species density and richness, suggesting that variations in bird species density is not a function of distance to the source of the SO_2 air pollution.

4.1.2 Determine the environmental variables that affect the bird populations around Matimba and Medupi power station

Through remote sensing and GIS analysis we successfully determined the environmental variables that affect the bird populations around Matimba and Medupi power station. Our findings revealed that habitat structure and vegetation productivity (remotely sensed variables) are the main environmental variables affecting bird species density and diversity variations. Habitat structure plays an important role in assessing bird species density and diversity patterns due to its relationship with critical variables such as foraging sites, nest placement and shelter from predators (Hutto, 1985; Martin, 1993). Birds make habitat selection decisions based on the vertical and horizontal structural characteristics of vegetation. Thereby making habitat structure a key environmental factor. Our results support the biodiversity hypothesis (MacArthur, 1961) that habitat structure and productivity are primary drivers of avian biodiversity.

4.1.3 Determine the current influence of SO_2 polluted air on bird population density and species diversity prior to the commencement of operations at Medupi power station

Results from this study showed that the current SO_2 concentration levels appeared to have no influence on bird species density and diversity variations around Matimba and Medupi power station. Habitat structure and vegetation productivity best explained the variation in the densities and diversity of birds around Matimba and Medupi power station. These findings were similar to that of Turner (1982) who found that the densities of *Delichon urbicum*, *Apus apus* and *Hirundo rustica* showed better correlations with the habitat type than SO_2 concentrations levels. However, this may or may not change once Medupi power station has been commissioned. Aermod dispersion model predictions were that SO_2 concentrations levels will increase significantly when operations at Medupi power station commence and this may create an unfavourable atmosphere for birds resulting in a possible decline in bird populations around Lephalale.

At a species level, our findings showed that SO_2 air pollution currently has no significant effect on the densities of individual species. Although the *Batis molitor* and *Streptopelia senegalensis* both exhibited a negative correlation with SO_2 air pollution, the SO_2 concentration levels were not high enough to influence significant changes in the densities of these two species. Habitat structure was established to have a more significant effect on the densities of these two species than SO_2 concentration levels.

4.1.4 Establish a baseline against which future studies can assess the influence of SO_2 air pollution on birds once Medupi power station is fully operational

Our results have established a baseline in which we can monitor the interactions between SO_2 concentration levels and bird population changes. Our findings can be analysed together with future monitoring data once operations at Medupi power station have commenced so that we can draw more comprehensive conclusions regarding bird community responses to varying SO_2 concentration levels. Understanding the relationship between SO_2 concentration levels and bird population changes will assist in formulating practical strategies in the monitoring and management of bird populations around coal burning power stations.

4.2 Limitations

- There were a few limitations evident in this study. Due to time constraints, financial constraints and inaccessibility, this study used a relatively small sample size, therefore there was less data for statistical inference. However, this can be solved by the adding more sample sites in future studies and assimilating the results of these studies with our study through meta-analysis.

- Bird counts can only assist in identifying species which are most sensitive to pollution as their populations would have already shrunk in size. However, bird counts cannot reveal the species that are potentially at risk in polluted areas.

4.3 Recommendations

- Behavioural responses by birds are not always as a result of the direct exposure to air pollution. Indirect effects of air pollution can reduce reproduction rates among bird species through depreciation in habitat quality. Therefore it is recommended that further research should be conducted to look at the effects of SO_2 air pollution on food resources for birds as well as the effect of SO_2 air pollution on vegetation productivity as primary productivity has an influence on the bird species richness patterns.

- Monitoring of bird populations should continue before the commissioning of Medupi power station and after operations at Medupi have commenced as this will facilitate in the selection of sensitive and relevant species for future impact ecology studies at other coal-fired power stations.

- Future studies at Matimba and Medupi power station should also focus on sites with high SO_2 concentration levels and incorporate the results of these studies with our study through meta-analysis so as to have a more comprehensive understanding on the relationship between bird species densities and SO_2 air pollution.

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APPENDICES

APPENDIX A: BIRD SPECIES RECORDED AT STUDY SITES DURING THE SAMPLING PERIOD

Common name	Scientific name	Status	Relative Density (spp./ha)		
			Kalamahala Range	Anglocoal Bulklip Range	Manketti Nature Reserve
Acacia Pied Barbet	*Tricholaema leucomelas*	Common, near endemic resident		1.27	1.27
African Grey Hornbill	*Tockus nasutus*	Common resident			1.27
African Hoopoe	*Upapa africana*	Common resident	3.82	6.36	15.27
Arrow-marked Babbler	*Turdoides jardineii*	Common resident	5.09	7.64	7.64
Banded Martin	*Riparia cincta*	Intra African migrant			6.36
Bar-throated Apalis	*Apalis thoracica*	Common resident	2.55	2.55	3.82
Bearded Woodpecker	*Dendropicos namaquus*	Common resident	3.82		1.27
Black-collared Barbet	*Lybius torquatus*	Common resident	1.27		
Blacksmith Lapwing	*Vanellus armatus*	Common resident	2.55	3.82	5.09
Blue Waxbill	*Uraeginthus angolensis*	Common resident	12.73	63.64	61.09
Bronze Mannikin	*Spermestes cucullatus*	Common resident			1.27
Brown-crowned Tchagra	*Tchagra australis*	Common resident		20.36	3.82
Brown-throated Martin	*Riparia paludicola*	Common resident	44.55	7.64	

Common name	Scientific name	Status	Relative Density (spp./ha)		
			Kalamahala Range	Anglocoal Bulklip Range	Manketti Nature Reserve
Brubru	*Nilaus afer*	Common resident		5.09	5.09
Burnt-necked Eremomela	*Eremomela usticollis*	Common resident	1.27	2.55	
Cape Glossy Starling	*Lamprotornis nitens*	Common resident	1.27		5.09
Cape Sparrow	*Passer melanurus*	Common, near endemic resident	1.27	2.55	17.82
Cape Turtle Dove	*Streptopelia capicola*	Common resident	10.18	45.82	96.73
Chestnut-vented Tit-babbler	*Sylvia subcaeruleum*	Common, near endemic resident	1.27		
Chinspot Batis	*Batis molitor*	Common resident	1.27	49.64	53.45
Cinnamon-breasted Bunting	*Emberiza tahapisi*	Common resident		2.55	
Common Fiscal	*Lanius collaris*	Common resident	2.55		
Common Scimitarbill	*Rhinopomastus cyanomelas*	Common resident		7.64	15.27
Common Waxbill	*Estrilda astrild*	Common resident		3.82	17.82
Crested Barbet	*Trachyphonus vaillantii*	Common resident	5.09	5.09	2.55
Crested Francolin	*Dendroperdix sephaena*	Common resident	56	35.64	71.27
Crimson-breasted Shrike	*Laniarius atrococcineus*	Common, near endemic resident	24.18	59.82	48.36
Crowned Lapwing	*Vanellus coronatus*	Common resident	56	10.18	2.55

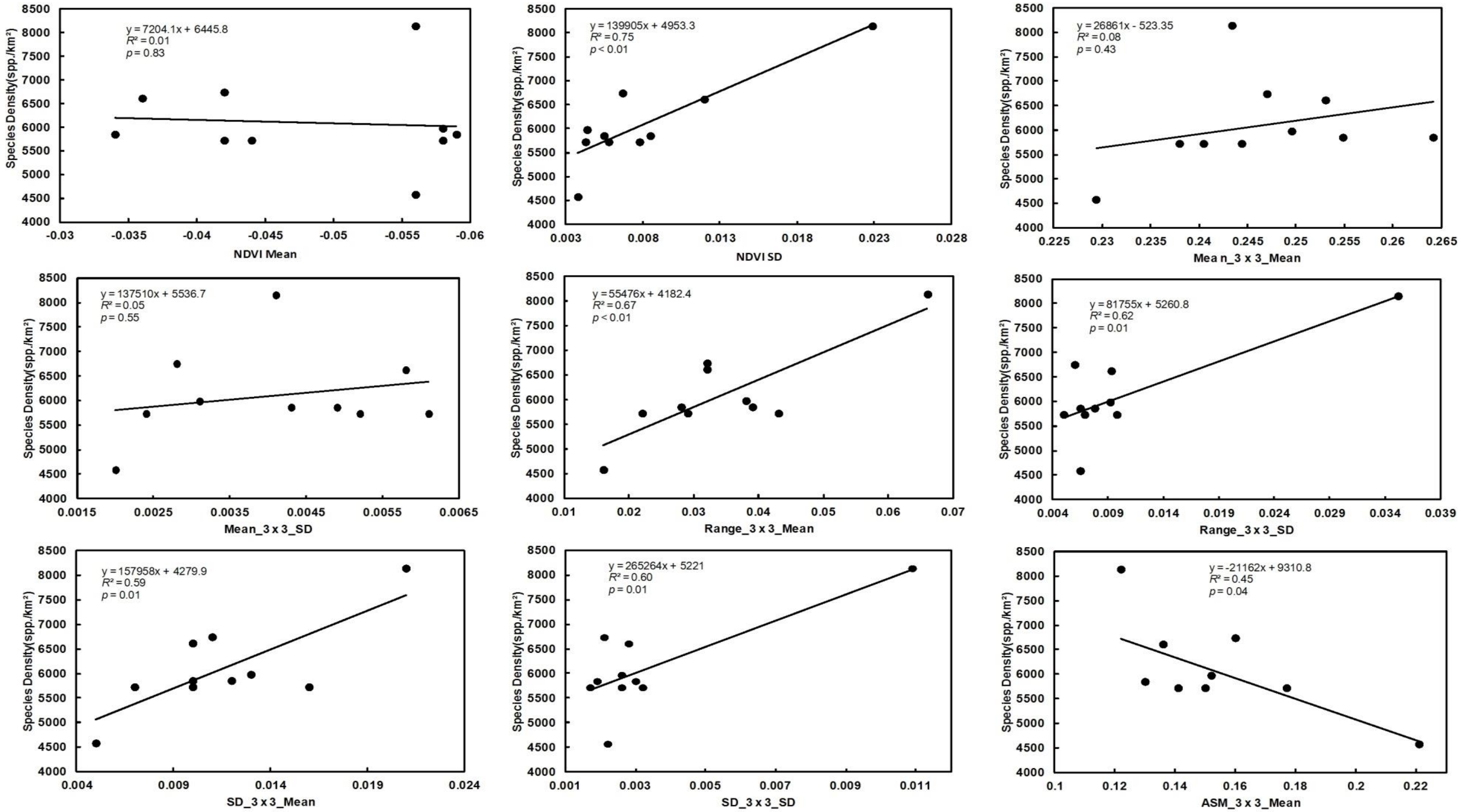
Common name	Scientific name	Status	Relative Density (spp./ha)		
			Kalamahala Range	Anglocoal Bulklip Range	Manketti Nature Reserve
Dark-capped Bulbul	*Pycnonous tricolor*	Common resident			2.55
Fork-tailed Drongo	*Dicrurus adsimilis*	Common resident	2.55		3.82
Golden-Breasted Bunting	*Emberiza flaviventris*	Common resident	1.27	2.55	1.27
Great Sparrow	*Passer motitensis*	Common, near endemic resident			5.09
Green Wood-hoopoe	*Phoeniculus purpureus*	Common resident		6.36	31.82
Green-winged Pytilia	*Pytilia melba*	Common resident			1.27
Grey Lourie	*Corythaixoides concolor*	Common resident	38.18	52.18	62.36
Hadeda Ibis	*Bostrychia hagedash*	Common resident	6.36	1.27	5.09
Helmeted Guineafowl	*Numida meleagris*	Common resident	22.91	5.09	40.73
Jameson's Firefinch	*Lagnosticta rhodopareia*	Common resident		1.27	2.55
Kalahari Scrub Robin	*Cercotrichas paena*	Common, near endemic resident		3.82	1.27
Laughing Dove	*Streptopelia senegalensis*	Common resident	39.45	10.18	6.36
Levaillant's Cisticola	*Cisticola tinniens*	Common resident			2.55
Lilac-breasted Roller	*Coracias caudatus*	Common resident	1.27	1.27	5.09
Little Bee-eater	*Merops pusillus*	Common resident	2.55	2.55	
Long-billed Crombec	*Sylvietta rufescens*	Common resident	2.55		1.27

Common name	Scientific name	Status	Relative Density (spp./ha)		
			Kalamahala Range	Anglocoal Bulklip Range	Manketti Nature Reserve
Long-tailed Paradise Whydah	*Vidua paradisaea*	Common resident	1.27	12.73	3.82
Magpie Shrike	*Corvinella melanoleuca*	Common resident	1.27	1.27	1.27
Marico Flycatcher	*Bradornis mariquensis*	Common, near endemic resident	1.27	5.09	1.27
Marico Sunbird	*Cinnyris mariquensis*	Common resident	1.27		1.27
Neddicky	*Cisticola fulvicapilla*	Common resident		5.09	3.82
Orange-breasted Bushshrike	*Chlorophoneus sulfureopectus*	Common resident	5.09	5.09	2.55
Pin-tailed Whydah	*Vidua macroura*	Common resident	1.27		
Purple Roller	*Coracias naevius*	Common resident			1.27
Rattling Cisticola	*Cisticola chiniana*	Common resident		14	15.27
Red-billed Buffalo Weaver	*Bubalornis niger*	Common resident		1.27	
Red-eyed Dove	*Streptopelia semitorquata*	Common resident	3.82		
Red-faced Mousebird	*Urocolius indicus*	Common resident	3.82	8.91	8.91
Sabota Lark	*Calendulauda sabota*	Common, near endemic resident	2.55	1.27	1.27
Scaly-feathered Finch	*Sporopipes squamifrons*	Common, endemic resident		1.27	

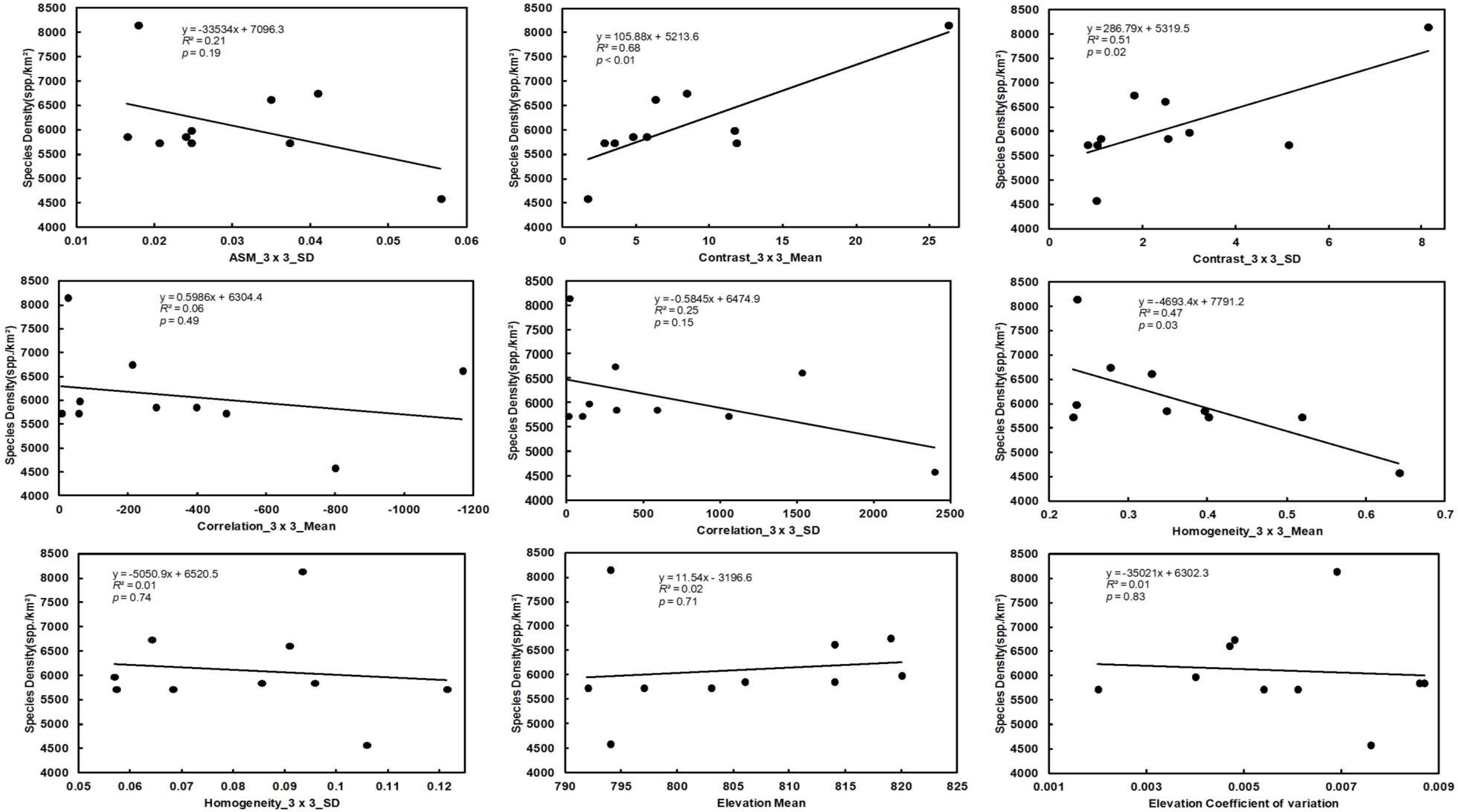
Common name	Scientific name	Status	Relative Density (spp./ha)		
			Kalamahala Range	Anglocoal Bulklip Range	Manketti Nature Reserve
Shaft-tailed Whydah	*Vidua regia*	Common, near endemic resident		10.18	3.82
Southern Masked Weaver	*Ploceus velatus*	Common resident	2.55	5.09	1.27
Southern Pied Babbler	*Turdoides bicolor*	Common, endemic resident		8.91	11.45
Southern Red-billed Hornbill	*Tockus erythrorhynchus*	Common resident	2.55		
Southern White-crowned Shrike	*Eurocephalus anguitimens*	Common, near endemic resident	3.82		
Southern Yellow-billed Hornbill	*Tockus leucomelas*	Common, near endemic resident	29.27	5.09	5.09
Streaky-headed Seedeater	*Crithagra gularis*	Common resident			10.18
Swallow-tailed Bee-eater	*Merops hirundineus*	Common resident	7.64	2.55	22.91
Violet-eared Waxbill	*Granatina granatina*	Common, near endemic resident			1.27
White-browed Scrub-robin	*Cercotrichas leucophrys*	Common resident			6.36
White-winged Widowbird	*Euplectes albonotatus*	Common resident	3.82		

APPENDIX B: SCATTER PLOTS OF THE RELATIONSHIPS BETWEEN BIRD SPECIES DENSITY AND ENVIRONMENTAL VARIABLES

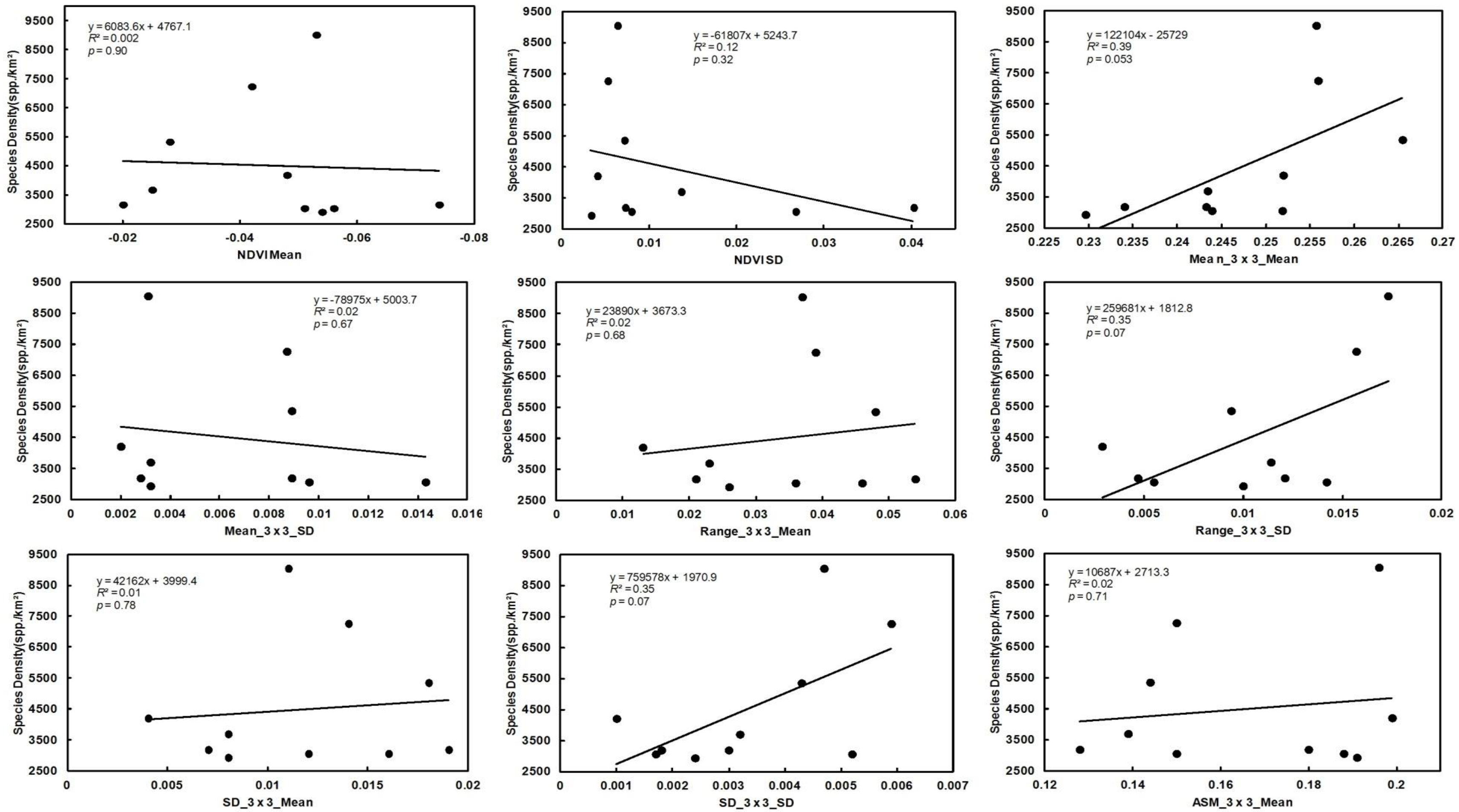
<u>Anglocoal Bulklip Range (a)</u>



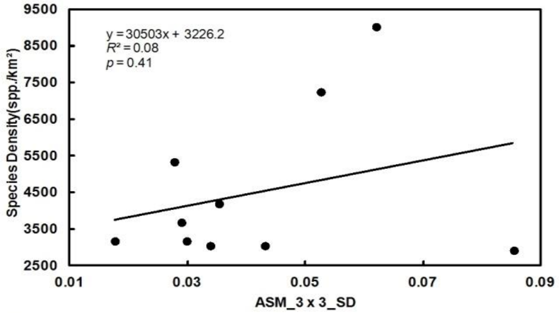
Anglocoal Bulklip Range (continued)

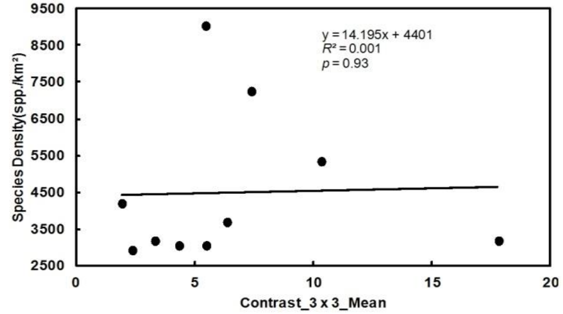


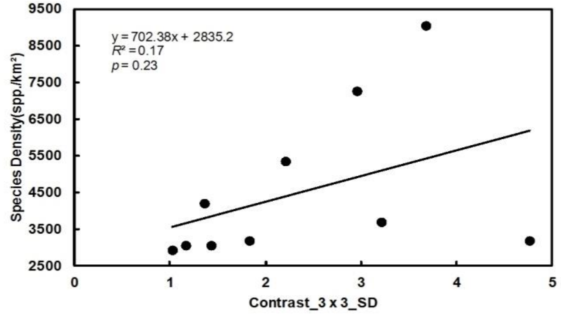
Kalamahala Range (a)

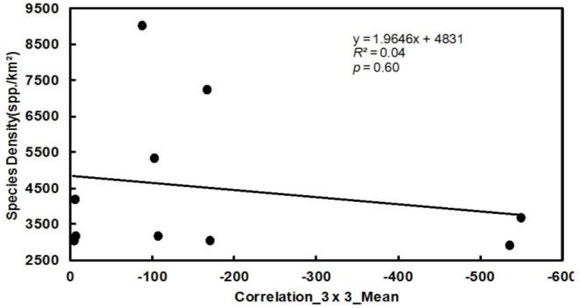


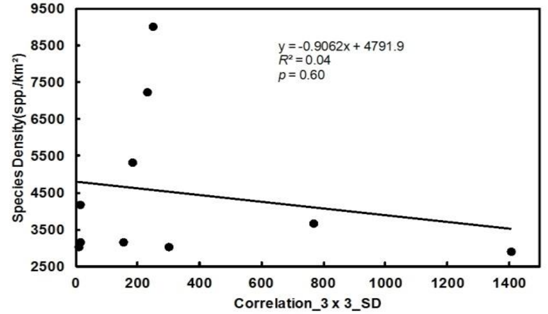
Kalamahala Range (continued)

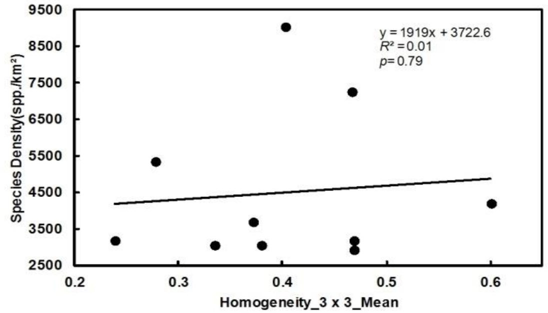


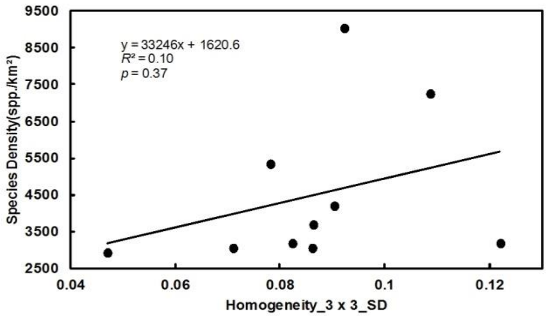


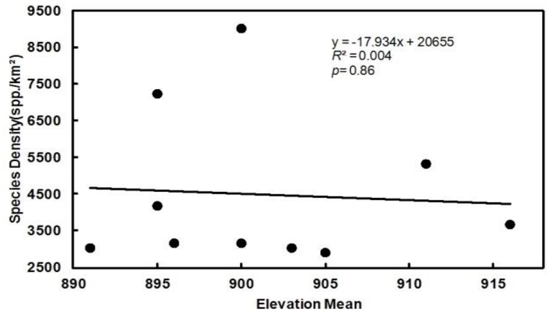


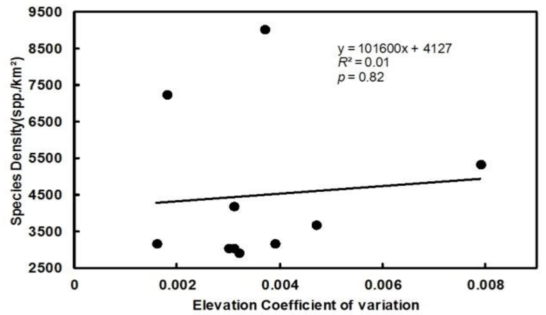




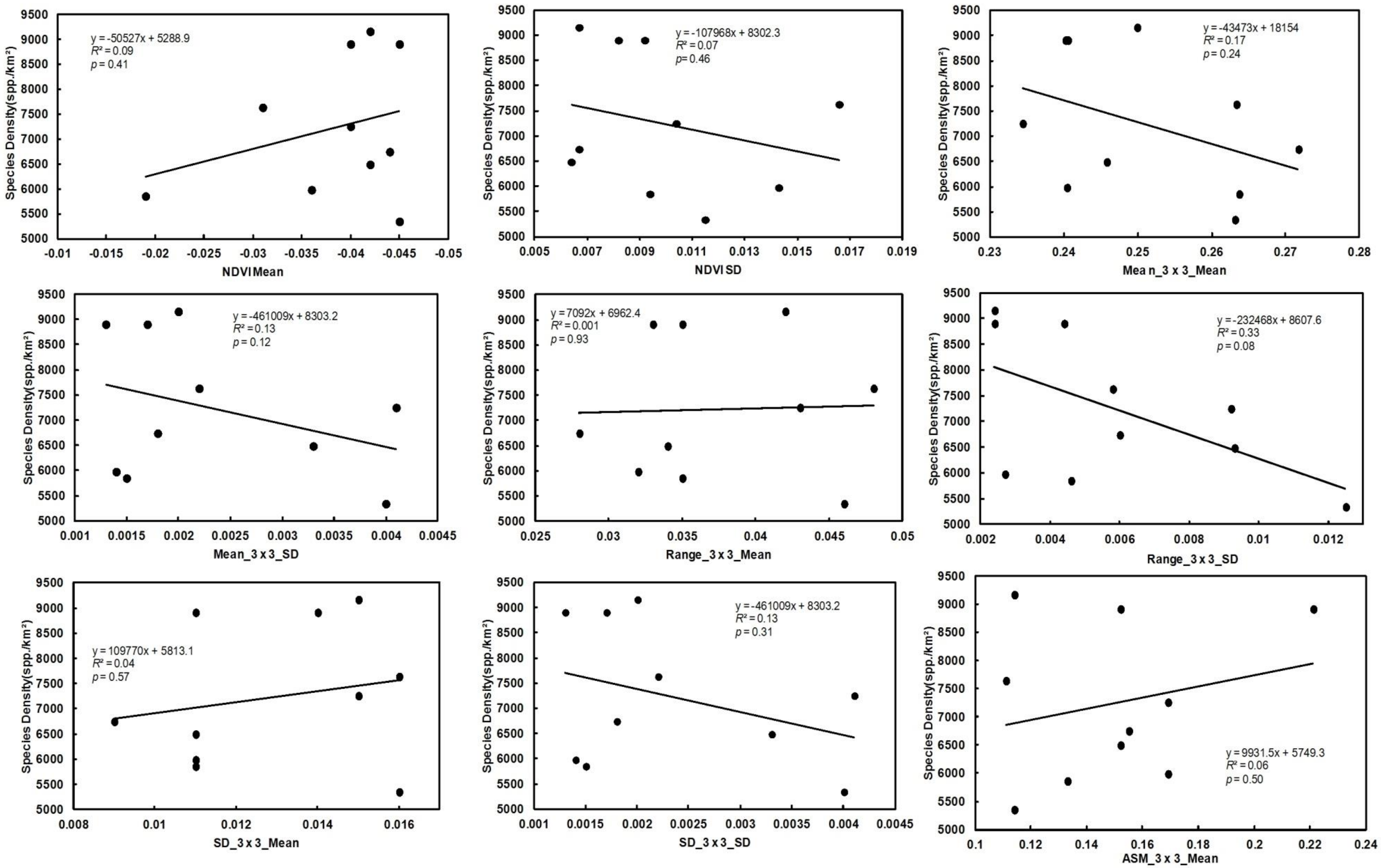




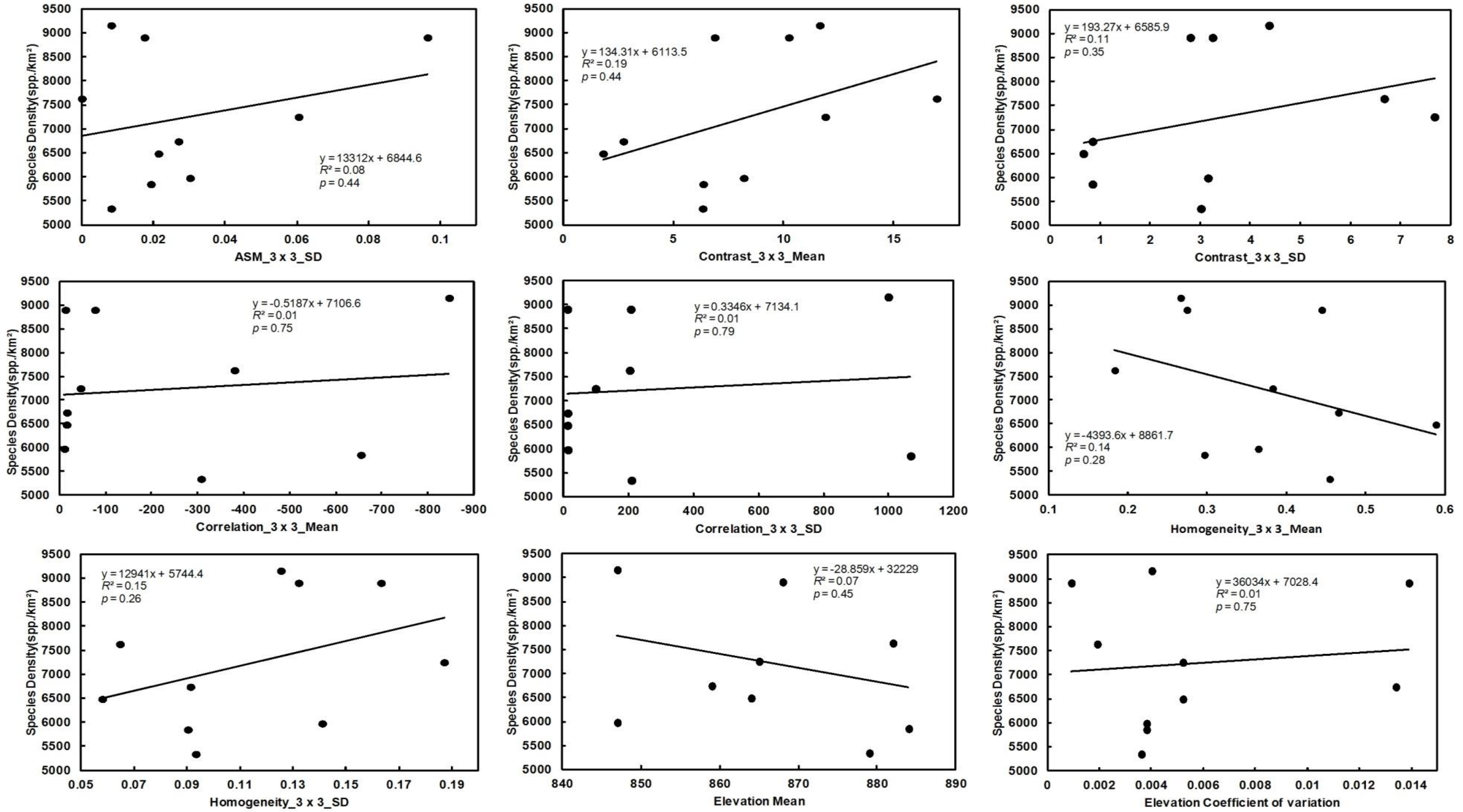




Manketti Nature Reserve (a)

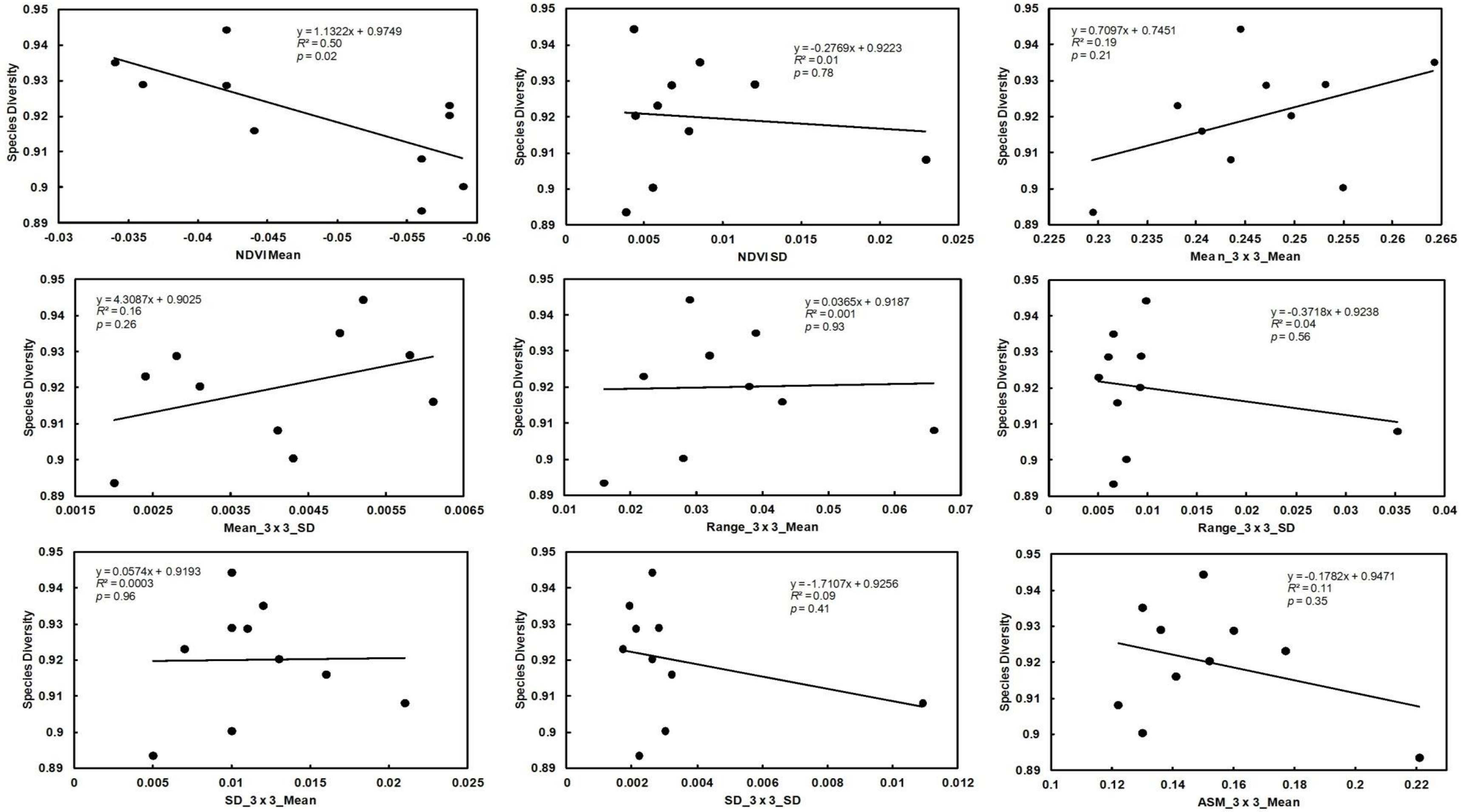


Manketti Nature Reserve (continued)

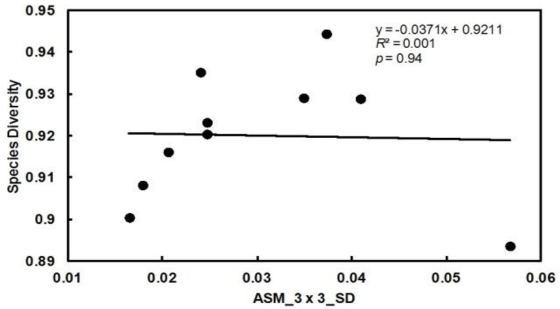


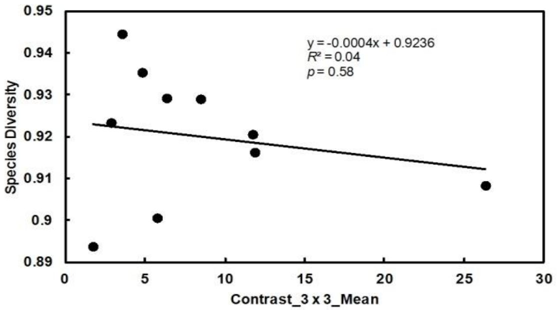
APPENDIX C: SCATTER PLOTS OF THE RELATIONSHIPS BETWEEN BIRD DIVERSITY AND ENVIRONMENTAL VARIABLES

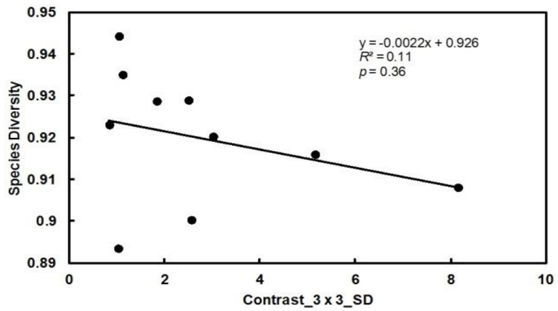
<u>Anglocoal Bulklip Range (a)</u>

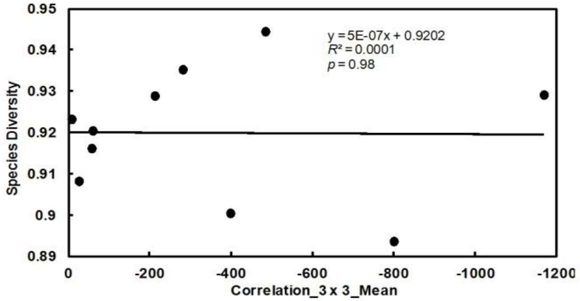


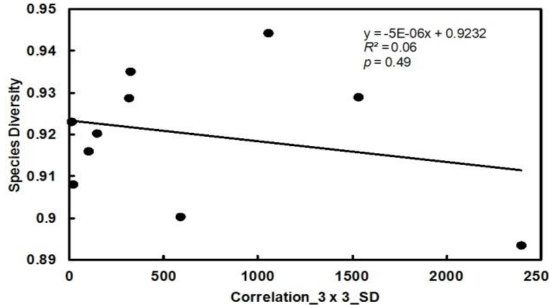
Anglocoal Bulklip Range (continued)

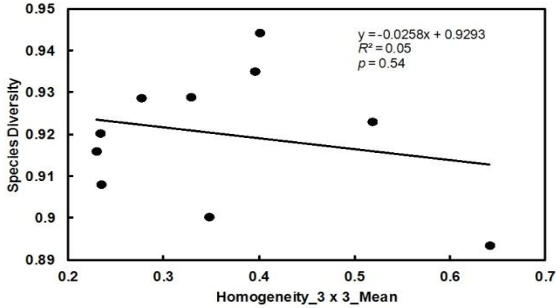


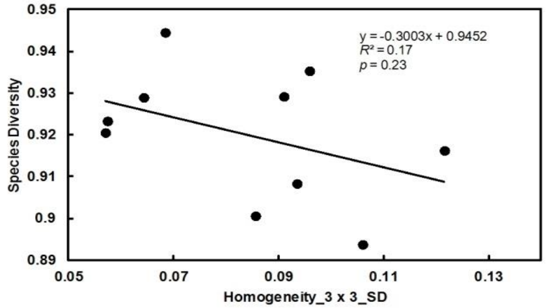


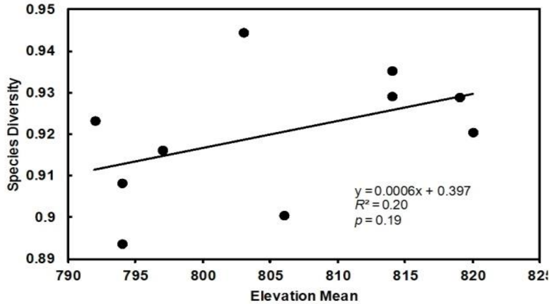


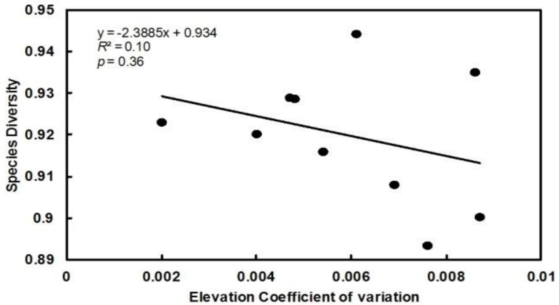




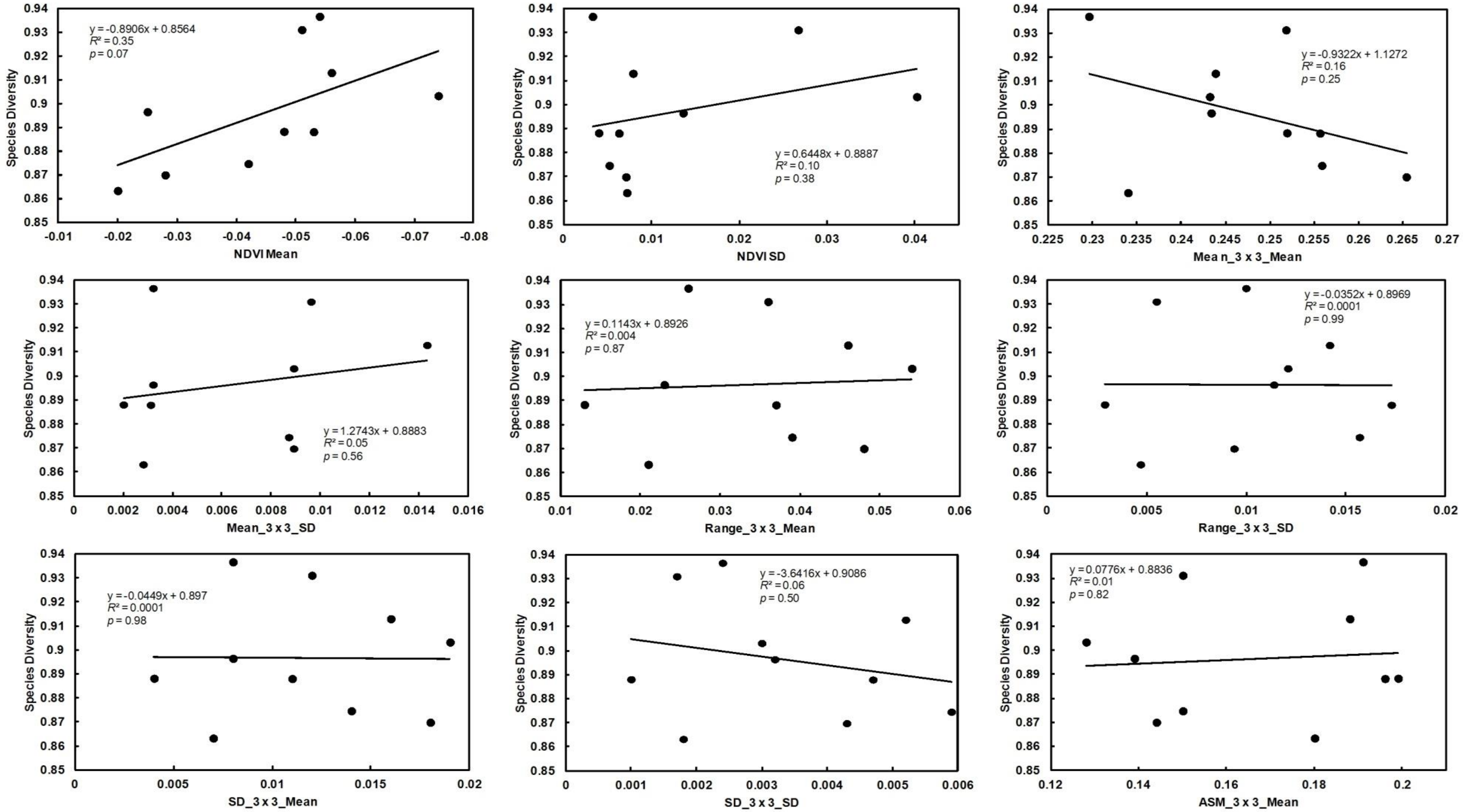




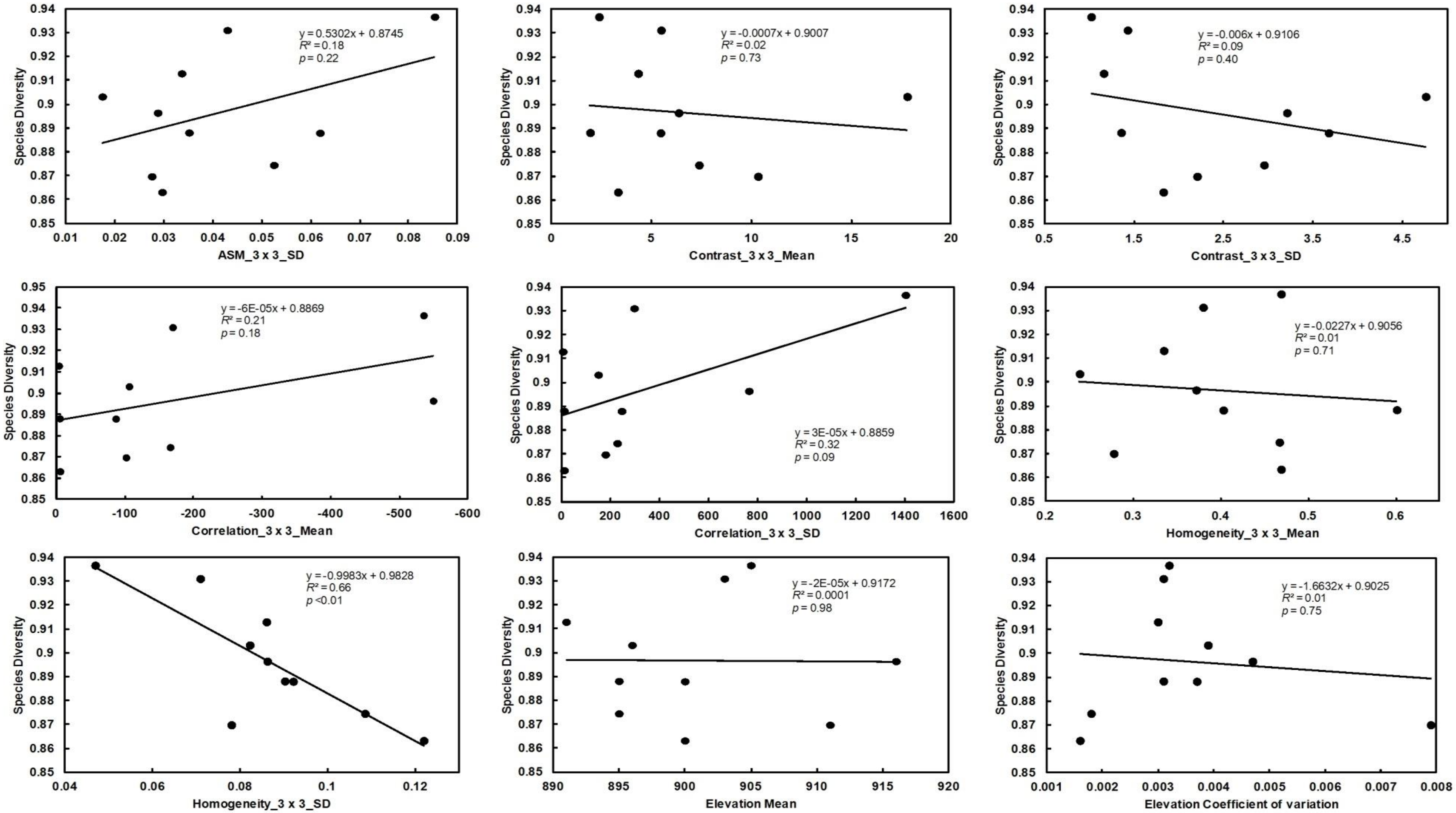




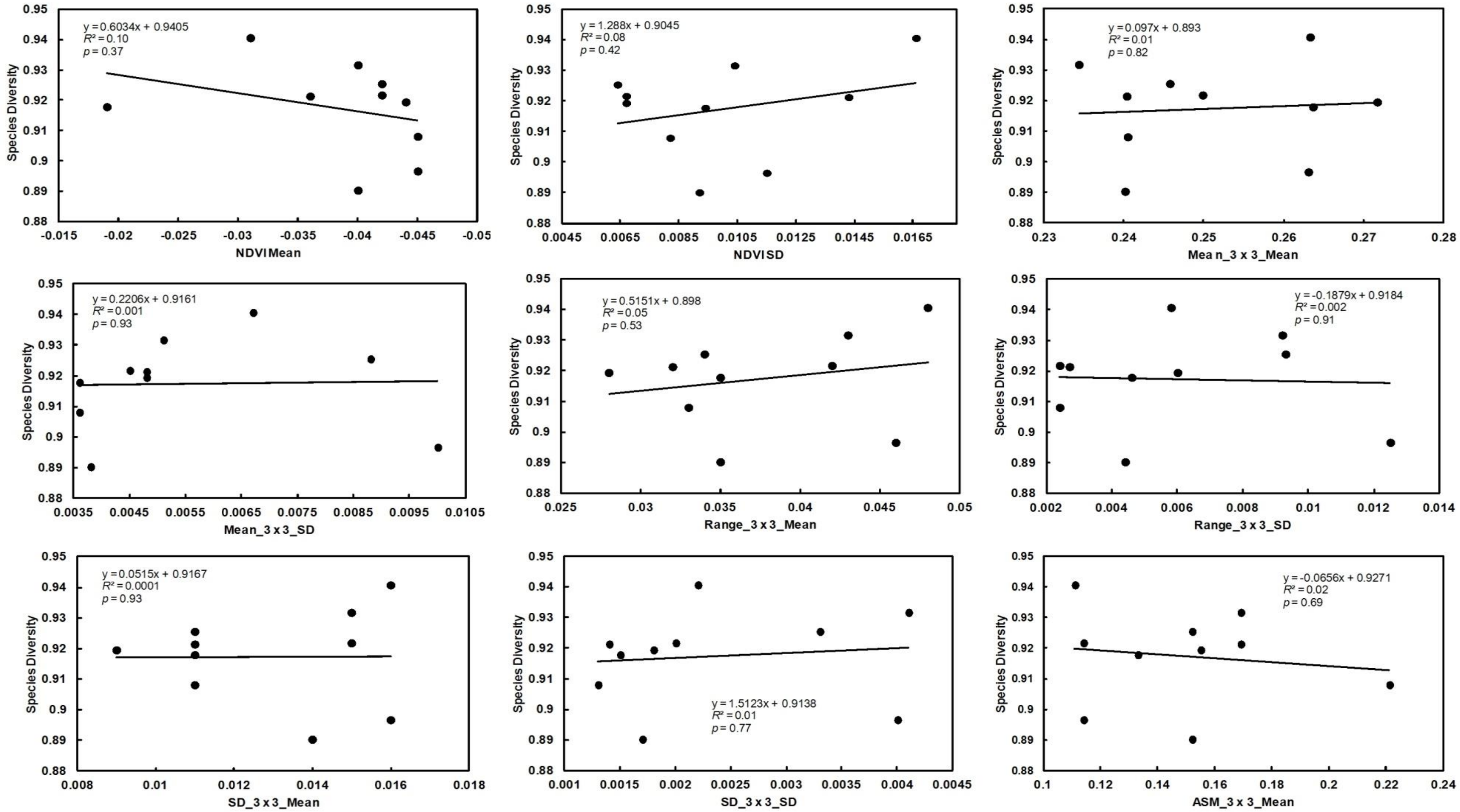
Kalamahala Range (a)



Kalamahala Range (continued)



Manketti Nature Reserve (a)



Manketti Nature Reserve (continued)