A systematic conservation plan for threatened freshwater wetland-dependent waterbirds across South Africa

By

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Abstract

Freshwater ecosystems are valuable to all components of biodiversity communities. Globally, these ecosystems are threatened by human activity and as a consequence, many vertebrates, including waterbirds, have become threatened. Wetlands are one of the most productive ecosystem types in the world. Yet, despite this, many protected area networks around the world fail to include this ecosystem type in their protected area networks. On a national scale, in South Africa, wetland loss and deteriorating wetland habitat quality continues to restrict and reduce the range of wetland waterbirds. For this thesis, Maximum Entropy (MaxEnt) species distribution modelling was used to identify additional areas of possible waterbird occurrence. The MaxEnt results noted that waterbirds rely on a combination of these environmental variables for their distribution ecology in their wetland habitat, with vegetation and humidity variables having the highest predictive powers. These would be considered important predictor variables for the distribution ecology of these waterbirds.

The National Freshwater Ecosystem Priority Area (NFEPA) project, a national freshwater conservation plan for South Africa, has not considered threatened wetland waterbirds in the identification of priority wetlands. Additionally, the existing protected area network fails to adequately protect the waterbird conservation features. A Marxan-based systematic conservation planning approach was used, accompanied by Maximum Entropy (MaxEnt) species distribution modelling to assess how well the existing Important Bird Areas (IBA's), the formally protected areas and Protected Area Network (PAN)(which is a combination of the IBA and formally protected area network), adequately protects the threatened wetland-dependent waterbird species.

The Bird Life South Africa 2018 checklist was used to identify the 11 threatened wetland-dependent waterbird species for this analysis. Due to insufficient sample records, one of the waterbird species, the White Winged Flufftail was removed from the analysis. Additionally, observation-based distributions from the South African Bird Atlas Project 2 (SABAP2) data was used to model species ranges in MaxEnt, along with vegetation and bioclimatic variables. All MaxEnt models were acceptable as all of the Area Under the receiver operator Curves (AUC) values were above 0.7. These observation- and modelled-based distributions were used in Marxan as conservation features. Conservation targets were assigned according to the threatened category of species. A Marxan cost variable was derived from an integration of Eskom powerlines, renewable energy and national landcover datasets.

A gap analysis of the Important Bird Areas (IBAs), formally protected areas and the Protected Area Network (PAN) was conducted. The PAN is the combined IBA and the formally protected areas. All three networks failed to adequately protect the 10 threatened waterbird species considered in this study. A Marxan best solution was used to identify planning units of high ecological integrity required to meet targets. Marxan was also used to expand the current PAN to adequately meet all conservation targets not met in the PAN. This expanded network was termed the PAN expansion. The Marxan best solution 2 and PAN expansion adequately met all of the conservation targets. Compared to the other 4 reserve networks, the Marxan best solution 2 was the least costly and it contained several areas of key IBAs and protected areas which are valuable areas for waterbird ecology. Although several planning units from the Marxan best solution 2 falls within key IBA areas and formally protected areas, several planning units that are not IBAs or formally protected areas could potentially complement the existing IBA and formally protected area network. The addition of these complementary planning units to the IBA and protected area networks could assist these two networks in adequately protecting the 10 conservation features.

Declaration

I declare that: ***A systematic conservation plan for threatened freshwater wetland- dependant waterbirds across South Africa*****is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.**

Neil Daniels **November 2020**

Signed: ………………………………………

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1 Introduction

1.1 Conservation of freshwater ecosystems

Nearly 70% of the world's surface area is covered by water and 2.5% of this is freshwater (Revenga et al. 2005). Despite this small contribution, 44000 of the 1868000 (6%) of the world's described species, depend on freshwater ecosystems for their habitat (Dudgeon 2006; Revenga et al. 2005). Human civilizations depend on freshwater ecosystems to function properly (Runge et al. 2009), and are especially valuable to the economic, cultural, scientific, and educational sectors (Poff et al. 2000; Sala et al. 2000; Driver et al. 2012). However, escalating human demands on freshwater systems cause increasing habitat loss, such that many freshwater and terrestrial ecosystems are under threat (Sala et al. 2000; Palmer et al. 2009). This is expected to increase exponentially in the future due to human population growth (Nel et al. 2009a).

Globally, the five main threats to freshwater biodiversity are overexploitation, water pollution, water flow modification, habitat degradation or destruction, and invasive species (Richter et al. 2010; Rivers-Moore et al. 2010). These five major threats combined have resulted in the reduction of both the range and population number of freshwater species (Groombridge and Jenkins 1998). On average, freshwater vertebrates' species ranges have been reduced by 54%, the majority of which are waterfowl (Groombridge and Jenkins 1998). On both global and local scales, the allocation of water for biodiversity conservation is usually disregarded (Standford 2003). For example, 55% of the world's largest dams are located in areas where no thought has been given to the downstream flow of water for biodiversity (Tharme 2003).

1.2 Wetlands

Wetlands contribute 4-6% of the earth's surface and are regarded as one of the most productive ecosystem types (Davidson 2014). In the 20th century, it has been calculated that half of all natural wetlands have been lost due to agriculture and urban sprawl (Davidson 2014). Conversely, many artificial wetlands, such as farm dams and sewerage networks have been created (Brown and Magoba 2009). However, the ecological benefits of artificial wetlands is small in comparison to that of natural wetlands (Brown and Magoba 2009). The benefit of natural wetlands is the provision of various services to biotic communities and the surrounding environment, such as sediment and nutrient storage, flood management and food-chain regulation (Doprado et al. 1994; Bolund and Hunhammer 1999). Wetlands are one of the ecosystem types that are seldom included in a formal protected area network design (Department of Environmental Affairs 2016). Consequently, in the water scarce regions of South Africa, waterbirds are an important indicator species, and their declining numbers is of concern (Rockstrom et al 2010).

Wetlands, in particular, play an important role in peoples' livelihoods through the provision of ecosystem services such as water purification, carbon storage, and slow release to prevent flooding. (Higgins et al. 2005; Dudgeon 2006).Benefits include direct services, water purification or bio-indicators for water quality and quantity (Higgins et al. 2005; Davidson and Finlayson 2007). Birds are often used as bio-indicators to assess the quality of the landscape. Their mobility can be used to indicate the quality and changes in habitats and landcover (Birdlife International 2012; Brandt and Glemnitz 2014).

1.3 Waterbirds

Waterbirds include all species that rely on freshwater ecosystems for foraging and exclude all species such as passerines, terrestrial birds, raptors and seabirds (Taylor et al. 2015). Waterbirds are key contributors to the functioning of ecosystems and biodiversity (Runge et al. 2009). Certain species may be classified as apex predators in wetlands trophic dynamics and play key roles in the populations of prey species (Smith et al. 2002). Wetlands for waterbirds include food provision, nesting material as well as breeding and roosting habitats (Abell et al. 2002). Wetlands are seasonally dynamic therefore which wetlands are conserved as protected networksarecrucial for the conservation of water bird guilds(Runge et al. 2009).In recent years waterbirds have experienced both declining abundance and reduced amounts of wetland habitat(Brown and Magoba 2009). Many studies show how the land-use changes affect the health of waterbirds (Abell et al. 2002). For example, mining activities changes air quality; this in turn affects the muscle tissue of waterbirds, causing them to move away and makes them the first indicator of a change in environmental condition (Sekercioglu et al. 2004). The loss of natural wetland ecosystems has resulted in waterbirds utilising temporary and artificial wetlands more frequently (Brown and Magoba 2009).

1.3.1 Eskom powerlines

There are over 350 000km of powerlines in South Africa and this number is expected to increase due to the 2030 National Development Plan highlighting the need for electricity for all South African citizens (National Development Plan 2012). The Strategic Integrated Projects (SIPs) launched as part of the NDP, identified SIPs 8 and 9 (Expansion of the wind and solar (PV) energy) and 10 (Electricity grid infrastructure expansion) in support of this national need for electricity (National Development Plan 2012).

Many published and unpublished studies indicate collision and electrocution threats of Eskom powerlines to several wetland waterbirds (Jenkins et al. 2008). Large birds in particular are more prone to collision, e.g. Cranes species (Jenkins et al. 2008). The Eskom and Endangered Wildlife Trust (EWT) Strategic Partnership was established in 1996 to develop and initiate a collaborative management system to decrease negative interactions between wildlife and electricity infrastructure (Jenkins 2008). This has been a successful initiative (Jenkins et al. 2008). Using national collision and electrocution data to identify areas of high collision and electrocution occurrences, the risk collision model products have resulted in far fewer waterbird collisions and electrocutions (Jenkins and Smallie2009). The results have created a blueprint for Australian avian conservation efforts (Taylor et al. 2015).

1.3.2 Renewable energy

The Endangered Wildlife Trust (EWT) and Birdlife have established many site-specific areas to monitor the negative impacts of wind energy farms on bird diversity and their habitat (Strickland et al. 2001). The increase in the use of wind as an energy source is expanding rapidly in South Africa (Jenkins et al. 2015). International literature suggests that the placement of wind farms has led to habitat destruction, displacement of many bird populations away from preferred habitat and collision with wind turbines (Jenkins et al. 2015). Wetland-dependent birds are regarded as the most vulnerable to this threat (Jenkins et al. 2015). Concentrated Solar Power (CSP) developments have introduced high incidences of collision rates (Frantzeskaki et al. 2002). CSP plants have degraded large tracts of natural habitat and have reduced habitat quality by using up large volumes of water, leaving the habitat dry and the surrounding air and water polluted (Bates et al. 1996). Solar Photovoltaic (PV) plants require relatively large areas, taking up about 2- 5 ha per MW (Zhai et al 2012). Due to this large area requirement, many species, especially those with specific habitat range requirements, have ended up with even more restricted habitat ranges (Lindenmayer and Fischer 2006). Conversely, solar PV sites have also provided nests and shade for some species (Frantzeskaki et al. 2002).

1.3.3 Habitat loss

Landcover was used to estimate habitat loss and areas unavailable for waterbird conservation for this study. Waterbirds depend mostly on natural classes of landcover for feeding and breeding (Runge et al. 2009). Natural landcover types include waterbodies and vegetation types (Taylor et al. 2015). For example, the Lesser Jacana (*Micropara capensis*) depends on habitat partially flooded with water surrounded by sedge vegetation (Taylor et al. 2015). This specific type of habitat is an appropriate feeding and breeding condition for this species (del Hoyo et al. 1996). Areas of non-natural landcover are mostly unfavourable for most waterbird ecology, with the exception of cultivation landcover being important feeding grounds for birds such as the Grey Crowned Crane (Botha 2010). Other non-natural landcover categories typically include mines and plantations (Taylor et al. 2015). For example, the presence of land use activities such as mining have decreased water quality for many waterbirds. (Botha 2010).

1.4 Threats to waterbirds

Human population growth and the expansion of the economic sectors have contributed to the degradation of freshwater ecosystems across the globe, to the extent that the freshwater biodiversity is declining. Consequently freshwater systems are among the most threatened ecosystem types in the world (Jenkins and Joppa 2009; Nel and Driver 2012). In the majority of Red List species assessments, habitat loss is a consistent threat at various temporal and spatial scales (Rivers-Moore et al. 2010). Some waterbird species are more resilient than others to habitat loss e.g. Grey Crowned Cranes (*Balearica regulorum*) have adapted to matrices of croplands and natural vegetation (Taylor et al.2015). However, some species may depend on a certain environmental condition for a portion of their annual life cycle, e.g. the Pink Backed Pelican (*Pelecanus rufescens*) rely on annual flooding events in the December/January periods for the onset of their reproductive cycle (Taylor et al.2015). The absence of this environmental condition lead to a decrease in species diversity (Freemark and Kirk 2001). Habitat loss also has drastic effects on isolated populations depending on limited resources that are not equally distributed in the landscape. Consequently, there is a need to effectively conserve the ecological integrity of these crucial habitats used by these waterbirds at both local and regional scales (McPherson and Jetz 2007). Three main sources of habitat loss for wetland birds were focused on in this study; viz. Eskom powerlines, renewable energy developments (wind and solar) and non-natural landcover (which includes mining, cultivation, plantations and urban built-up areas).

1.5 National freshwater conservation planning in South Africa

Approximately 25% (close to 2600 species) of the world's bird species undergo at least some type of seasonal movement, this may be across different landscapes and even continents (Runge et al. 2009). Traditionally, the science of conservation has a tendency to assume that the biodiversity features for management are static in space and time (Pressey 2004). Birds are typical examples of biodiversity features that are dynamic and have broad territory and large home ranges (Runge et al.2009). Conservation biology needs to fully engage in broader spatial and temporal scales (Pressey et al. 2007) in order for conservation planning to have relevance in the decision making process.

The National Freshwater Ecosystem Priority Areas (NFEPA) (Nel et al.2011; Turpie et al. 2012) is currently South Africa's most comprehensive national level conservation plan for freshwater biodiversity. This national freshwater conservation plan identifies priority rivers, wetlands and estuaries using a systematic conservation planning approach (Roux et al. 2008). These areas were termed Freshwater Ecosystem Priority Areas (FEPAs) and incorporated species associated with these priority areas, important ecological processes and conserving ecosystem types (Roux and Nel 2013). With regard to species, NFEPA selected threatened freshwater fish, threatened waterbird species, of which only Cranes (Wattled Cranes (*Bugeranus carunculatus*), Grey Crowned Cranes *(Balearica regulorum)* and Blue Cranes (*Anthropides paradisea*)) were specified as part of the selection criteria (Nel et al. 2011). The limitations of the aforementioned conservation plan signify a need for a national systematic conservation plan to identify important areas for the long-term conservation of threatened freshwater wetland waterbirds. Of the 141 waterbird species in South Africa, 19 are threatened or near threatened (13%) (Taylor et al. 2015). The areas of occupancy for many of these threatened species have seen steep declines over the past few years (Taylor et al. 2015). However, some waterbirds such as the Wattled and Grey Crowned Crane have several conservation efforts in place and have been included in provincial conservation plans, e. g. the Mpumalanga biodiversity sector plan (Lotter 2014) and the NFEPA (Nel et al. 2011).

1.6 IUCN Redlist Criteria

Before any conservation efforts can be put in place, some idea of the risk each species faces needs to be evaluated (Hoffman et al. 2008). The International Union for Conservation of Nature (IUCN) Red List scientifically assesses a group of species using a set of criteria (See Table 2) (Hoffman et al. 2008) (IUCN 2003). The IUCN criteria aim to determine risk factors to detect reasons as to why species are threatened using five criteria (IUCN 2003). These are reduction in population size, geographic range, population size, small population size and quantitative analysis (IUCN 2003; Taylor et al. 2005).The use of the IUCN Red List status is necessary because it provides guidelines on setting targets, which ultimately feeds into the level of representation and persistence needed in a reserve design system (Margules and Pressey 2000). The IUCN Red List assessment criteria is an international standard that was adopted by South Africa as it is a signatory to the Convention on Biological Diversity (CBD). The aforementioned list allows species threat status comparisons to be made and achieve progress on biodiversity at a global level (Hoffman et al. 2008).

1.7 Mechanisms used for planning

Key Biodiversity Areas (KBAs) are areas that contribute significantly to the persistence of global biodiversity (Taylor et al. 2015). These include important habitat for threatened plant and animal species in ecosystems such as terrestrial, freshwater and marine ecosystems (Taylor et al. 2015). Important Bird Areas (IBAs) are a group of areas that are recognized as important areas for bird conservation based on global threatened status, restricted ranges < 50000km², biome restricted assemblages and congregations of certain bird groups such as migratory waterbirds or breeding seabirds (Taylor et al. 2015). When the IBA network was established, it ensured that IBAs were a specific group of areas containing key resources for all birds (Coetzee 2008). IBAs were designed with the goal of overlapping with protected areas as much as possible in a region (Fishpool and Evans 2001). Important Bird Areas will also eventually be re-evaluated as KBAs (Marnewick pers. Comm).

Protected areas, by definition, are areas formally protected, as declared in terms of the National Environmental Management: Protected Areas Act (Act 57 of 2003) and are managed for biodiversity conservation (Department of Environmental Affairs 2016). The goal of protected areas is to include enough biodiversity components and ecological sustainability with resilience to threats like climate change and natural disasters (Jantke and Schneider 2010). Historically, protected areas were not planned systematically in terms of including areas with high priority biodiversity (Jantke and Schneider 2010). For example, in some areas of South Africa, protected areas such as Table Mountain National Park is located in mountainous areas for growing the tourism economy and not for its biodiversity value (Oldfield et al. 2004).New protected areas in South Africa are currently much better planned, with specific requirements, especially for contract Nature reserves (Jantke and Schneider 2010). The National Protected Area Expansion Strategy (NPAES) has made this possible by using new biodiversity data, which allows Provincial conservation plans to be updated (Department of Environmental Affairs 2016).

1.8 Protected Area Expansion Strategy

The purpose of the NPAES was to ensure that the PA network is expanded in order to protect representative samples of all ecosystem types (Ando et al.1998). In South Africa, the biodiversity stewardship programmes have been established to declare private land as protected areas (SANBI

2015). As part of the biodiversity stewardship programme, declared contract nature reserves have the same status as protected areas (Ando et al. 1998). A contract nature reserve is an agreement made between communal or private landowners and conservation authorities to manage and protect land in biodiversity priority areas (Taylor et al. 2015). These programmes have been effective in accomplishing this objective by achieving national protected area targets at far lower costs to the state than land acquisitions (Balmford et al. 2002). A total of 24 contract protected areas for stewardship have been declared through the programme, totalling 75000 ha of land (Taylor et al.2015). A lack of human resources has been a limiting factor in declaring new contract nature reserves and parks through the biodiversity stewardship programmes (Taylor et al.2015). Many organisations have initiated biodiversity stewardship programmes, which entail collaboration with private and communal land owners (Department of Environmental Affairs 2016). The goals of these collaborations are contractual agreements that assign protection status to parcels of land, with the creation of habitat corridors and a list of conservation goals to achieve (Taylor et al. 2015). For example, Ezemvelo KwaZulu-Natal Wildlife has initiated such programmes to legally protect private land as part of the National Protected Area's Expansion Strategy (NPAES) and KZNs provincial PAES strategy. (Department of Environmental Affairs 2016). Besides Nature reserves and protected environments, there are three other types of Biodiversity Stewardship Agreements, namely Biodiversity Management agreements, Biodiversity Agreements and Biodiversity Partnership Areas (SANBI 2015). Each of the five types of agreements has a different level of protection for biodiversity and land-use restrictions (SANBI 2015).

1.9 Systematic conservation planning

Due to the burgeoning economy and increasing landtransformation, numerous problems arise for the protection of existing biodiversity, and especially for freshwater wetland waterbird conservation (Rodrigues and Brooks 2007). Systematic conservation planning aims to identify a comprehensive network of suitable habitats that assist in protection of biodiversity (Margules and Pressey 2000). Systematic conservation planning consists of a set of principles to prioritize areas (habitats) for biodiversity (Margules and Pressey 2000). These principles minimize cost for biodiversity persistence and decrease the likelihood of selecting areas that compromise biodiversity persistence and integrity (Jantke and Schneider 2010). The process of systematic conservation planning has six stages, viz. compile the data, identify conservation goals, review existing protected areas, select additional protected areas, implement actions, and maintain the selected conservation areas (Margules and Pressey 2000; Holness and Biggs 2011).

Systematic conservation planning aims to address two main ecological objectives, namely identifying areas that are important for biodiversity representation and persistence (Possingham et al. 2002). These objectives are achieved by following a principle known as "CARE" - Connected, Adequate, Representative and Efficient (Possingham et al. 2006). Connectivity ensures that biophysical and ecological processes are transported between habitats in the connected reserve network (Margules and Pressey 2000). Adequacy ensures that there is enough of each conservation feature so that it persists through time (Pressey and Logan 1998). To elaborate, conservation features are any ecosystem type or species that is chosen to be included in a conservation plan (Possingham et al. 2002). Quantitative values, i.e. targets, are set by conservation planners for these conservation features (Margules and Pressey 2000; Hoffmann et al. 2008). Representivity aims to have several aspects of each conservation feature in the resulting reserve network to have more than one example of the conservation feature expressed in the reserve network. Representivity lowers the risk of a specific conservation feature becoming extinct (Margules and Pressey 2000). If a conservation feature needs more area or a range of different habitats this is taken care of by adjusting the amount of representivity. Efficiency refers to the ability of systematic conservation planning to maximize conservation gains at the lowest possible cost against sectors that compete for the same space (Williams et al. 1996; Possingham et al. 2002; Holness and Biggs 2011).

Internationally, the practice of conservation planning in general does not incorporate the systematic approach with new reserves often contributing very little to biodiversity (Margules and Pressey 2000). Reasons for this include competition for land among various sectors such as conservation, housing and development and various other industries (Pressey and Logan 1998). Due to the government and other industries using the land, many forms of existing biodiversity coexist with human built structures in remnants of land in poor ecological condition; or exist in moderate landscape conditions, but lack key resources (Margules and Pressey 2000).

South Africa has been recognized as a global leader in real-world systematic conservation planning (Balmford 2003). South Africa has applied systematic conservation planning to a wide range of spatial planning and decision-making processes (Botts et al.2019). Previously in South Africa, the practice of conservation planning was strongly concentrated in the academic realm (Knight et al.2008). Over the past three decades, there has been an increased focus on implementing academic knowledge and expertise into a more applied domain of conservation planning (Botts et al.2019). Non-Government Organisations (NGOs) are non profit groups that work independently from the government (Roux et al.2011).NGOs have been instrumental in providing government agencies with the technical skills and ecological understanding to produce conservation plans (Roux et al.2011). South Africa has strived to integrate conservation planning into laws and policies which can ultimately result in legislative changes for biodiversity (Botts et al. 2019). The process of systematic conservation planning in South Africa involves strong stakeholder engagement and includesthe local and scientific communities in the planning process (Holness and Biggs 2011). Stakeholder engagement allows an informal and neutral peer review approach, which consequently allows criticism and assessments against inappropriate decision making (Holness and Biggs 2011). The practice of systematic conservation planning in South Africa also focuses on standardizing the aspects of planning which promotes its implementation (Botts et al. 2019). An example is the agreed upon legend categories for the Critical Biodiversity Areas so that management objectives are similarly expressed across the provinces (Botts et al. 2019).

For any conservation plan, dividing the entire study region into smaller manageable areas is necessary for a robust analysis (Day et al. 2003). These small subdivided areas are called planning units and are defined as the primary components of a reserve system (Day et al. 2003). After being allocated different levels of biodiversity value, certain planning units are favoured above others, when determining the important areas for the final reserve network (Braatz 1992; Nel et al. 2011). The choice of the size and shape of planning units is driven by the nature of the planning task (Abell et al. 2007). Overall,planning units are advised to be small and consistent in size, and have a consistent perimeter to area ratio (Ardron et al. 2010).

The selection of additional areas to current PANs are often aided by decision-support software and algorithms (Margules and Pressey 2000). Several useful conservation planning software packages or decision-support softwarehave been developed with C-Plan (the original software conservation planning tool), Marxan and Zonation (currently the most widely used approaches with the Zonation being a refinement) andCLUZ (Conservation Land-Use Zoning software which is a plugin for Q-GIS that broadly does the same as Marxan), which is the most widely used (Game and Grantham 2008). Marxan is used for terrestrial and marine conservation planning in over 180 countries (Watts et al. 2009). Marxan functions to select the fewest planning units that represent the target value for biodiversity at minimum cost (Ball et al. 2000). It sets itself apart from other software as it delivers a spatially clustered set of good solutions using simulated annealing (Game and Grantham 2008). Marxan is extremely useful in that it uses cost data that can contain different values and can be applied in a spatial context (Ball et al. 2009). Its optimization technique allows it to generate various numbers of “near-good” solutions suitable for the defined problem (Ball et al. 2009). Marxan’s flexible properties have solved several well-defined conservation planning problems all across the world (Ball et al. 2009).

Certain areas have higher levels of biodiversity integrity than others (Pressey et al.2002). Based on the state of biodiversity integrity and other considerations, each planning unit in Marxan can be assigned a certain cost value (Game et al. 2009). There are various ways to calculate the cost of every planning unit (Ardron et al. 2010). The area of the planning unit can be used as its cost, social or economic factors (such as land value). It can also be used to create an index of relative threat to biodiversity (Sarkar et al.2006). Cost values can also include estimated real estate values and basically are used to prioritize the assessment of the planning units to provide the most efficient solution (Sarkar et al.2006). The assignment of cost values gives Marxan options when selecting those planning units of lowest cost into its final reserve plan (Game et al. 2009). In order to use cost parameters, a cost surface layer usually includes multiple factors, which are often weighted based on either literature or expert advice for an accurate relative threat index to biodiversity (Ardron 2010).

In South Africa, conservation planning is based on the development of a Systematic Conservation Plan (SCP) which identifies the Critical Biodiversity Areas (CBA) as the final outcome (Driver et al. 2017). A CBA Map identifies a set of biodiversity priority areas referred to as Critical Biodiversity Areas (CBAs) and will also include Ecological Support Areas (ESAs) which augments the CBA (Driver et al. 2017). These CBAs and ESAs, together with protected areas, are what are required as a representative sample of all ecosystem types and species, in order for them to persist in the future (Driver et al. 2012). CBA Maps show a set of geographical areas used to inform planning, action and decision making for sustainable development (Driver et al. 2017). They are recommended to be used in a range of sectors such as land-use planning, environmental, agricultural and mining authorizations, and any other decisions that impact on the use and management of natural resources (Driver et al. 2017). CBAs are used by the biodiversity sector for activities such as protected area expansion or the restoration of critical ecosystems (Driver et al. 2017). The key input data used in generating CBA Maps include ecosystem types, threatened species, rare or range-restricted species, unique habitats, areas important for ecological processes, ecological infrastructure, protected areas, ecological conditions social constraints and opportunities (Driver et al. 2017).

1.10 Modelling species distributions

For effective biodiversity management, the geographical range of the species is a factor that needs to be explicitly defined (Dudik et al. 2004). Existing species-data based on location points are often insufficient for describing the overall likelihood of a species occurring in the landscape (Johnson et al 2004). Collecting species data from every potential habitat or site is expensive and time-consuming

(Zaniwski et al. 2002). Models have thus become useful by using environmental data to extrapolate areas where species could possibly occur (Zaniwski et al. 2002). This allows more informed decisions to be made with regard to species distribution across areas that are often difficult to access (Pearce and Boyce 2005).

Approaches used for ecological niche modelling include absence, presence-absence and presence data models (Peterson 2006). There has however been a growing interest in the use of presence-only environmental variable data (Peterson 2006). This presence-only approach includes where environmental data are present (Graham et al. 2004). It excludes data where species are not found (Graham et al. 2004).

Species modelling outputs have proved to be useful for many applications, such as accelerating field surveys, testing hypotheses and generating inputs for conservation planning (Fielding and Bell 1997; Elith et al. 2006). The aim of species distribution modelling is to determine areas where species are able to exist using known species distribution data as well as environmental variables (Pearson et al 2006). In niche modelling, there are two types of niches, namely realized and fundamental niches (Hutchinson 1957; Pearson et al 2006). The dataset representing the species' known distribution is a representation of its realized niche (Hutchinson 1957). The realized niche is a part of the fundamental niche of a species, after taking detrimental interspecific interactions into account (Hutchinson 1957). The fundamental niche is the full set of environmental conditions in which a species can survive or reproduce (Elton 1927). The accuracy of models in determining a species' full set of environmental conditions, also known as the fundamental niche, depends on how well environmental variables are able to define a species distribution limits (Anderson 2003). There are numerous modelling software packages available for species distribution modelling (Anderson 2003). However, for this study which contained present-only species distribution data, MaxEnt was used.

MaxEnt is a popular species modelling tool because of its ability to characterize probability distributions using incomplete information (Phillips et al 2006). MaxEnt formalizes a probability distribution across the study area, using species presence-only data and environmental data spread across the entire study area (Pearson et al. 2004; Elith et al. 2006). It allows the user to include background data, which are predictor variables and can be increased to substitute for speciesabsence data (Peterson 2006). MaxEnt generates an area of cells each containing a probability of species occurring in that specific grid cell (Pearson et al. 2004). The summed probability of all output cells sums up to a value of one (Phillips et al 2006). MaxEnt has had over 1000 published applications since 2006 (Merow et al. 2013). Its wide variety of settings has allowed users to generate more accurate species distribution models (Merow et al. 2013). For the aforementioned reasons above and the fact that MaxEnt accepts presence-only species data as input files, MaxEnt software became the most suitable software to use to generate species distribution models for waterbird species in this thesis.

1.11 Problem statement

Based on the Millenium Assessment, fresh water ecosystems and the biodiversity it contains was a global priority. In a semi- arid country like South Africa, wetlands not only provide useful services to humankind, but also serve as habitat for many waterbird species (Brown and Magoba 2009). Waterbirds can be utilized as a useful indicator species for both water quality and quantity (Brown and Magoba 2009). Due to habitat loss and degradation, many waterbird species ranges have been declining and restricting over the years (Taylor et al. 2015). In a dynamic mixed-use landscape, a systematic conservation planning approach was used to identify sites of high priority for waterbirds. Due to the dynamic mobility of waterbirds, ecological niche modelling is a useful tool for modelling observation-based records in order to generate likely distribution ranges for waterbirds (Zaniwski et al. 2002). This modelled distribution, along with observation-based records complements the systematic conservation planning approach (Driver et al. 2017). A Marxan-based systematic conservation planning approach (Ball et al. 2009) can be used in many situations including its application to the conservation of wetlands and waterbird populations (Stralberg et al. 2011). The sites identified via the systematic conservation plan could augment existing conservation plans(Driver et al. 2017) such as the Important Bird Area (IBA) network,the Key Biodiversity Areas (KBAs), the National Protected Areas Expansion Strategy (NPAES) and the CBA Map.

2 OverviewofAnalysis Protocol

2.1 Approach

A Systematic Conservation Planning (SCP) approach was used to assess how efficiently threatened waterbirds are conserved in South Africa. Systematic conservation planning offers a framework that is efficient and scientifically defensible by selecting spatial areas that are low in cost (Margules and Pressey 2000). Systematic conservation planning follows four ecological objectives, namely connectivity, adequacy, representivity and efficiency, also known as the "CARE "principal (Possingham et al. 2006; Ardron et al. 2010). Through these principles, SCP strives to prioritize areas for conservation, while simultaneously acknowledging the social and economic factors (Margules and Pressey 2000). The goal of this study was to meet the user-defined targets for all conservation features to ensure that they are all adequately represented in the various reserve networks. Conservation targets of 100%, 80% and 50% were assigned to (Critically Endangered) CR, (Endangered) EN, and (Vulnerable) VU threatened waterbirds respectively, for both observation and modelled distributions (Ardron et al. 2010). Integral to the overarching goal was the need to make the final conservation network design efficient by keeping the network well connected; represent all of the conservation features and adhere to low costing, while still adequately meeting the conservation feature targets (Ardron et al. 2010).

2.2 Aim of this thesis

The aim of the dissertation is to determine whether threatened waterbird species are adequately protected in South Africa, and if not, to design a complementary network of areas that would efficiently protect the under-represented species. The objectives are to generate niche models for each of the species; to test whether species meet their biodiversity targets in existing reserves; and if not, to identify complementary areas that meet targets for underrepresented species for the least cost in the most efficient design.

Aim1: To determine and map the distribution of threatened waterbirds in South Africa using species distribution modelling techniques.

Aim 2: Toassess the adequacy of the IBAs, protected areas and PANs in protecting the observed and modelled conservation features.

Aim 3: To assess the adequacy of a Marxan best solution in protecting the observed and modelled conservation features.

Aim 4: To assess which reserve network design adequately protects all of the 10 threatened waterbird species best and aligns the best with the CARE principles of Systematic Conservation Planning.

2.3 Research questions

Research question 1: What is the distribution of threatened waterbirds in South Africa?

Research Question 2: Using Arcmap 10.3, what is the condition of the South African landscape based on the 2013/14 DEA landcover used in this thesis?

Research Question 3: Does the existing IBA network adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 4: Does the existing protected area network adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 5: Does the existing PAN adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 6: Would a reserve network designed from conception using Marxan adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 7: Would an expanded PAN designed using Marxan adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 8:

Is the reserve network of Marxan the best reserve network configuration for the 10 threatened waterbirds? Or should the planning units of the Marxan solution be used to complement the existing IBA and protected area networks?

2.4 Objectives

Objective 1: Use known locations and environmental predictors (MERRAclim Bioclimatic variables (1-19) and Mucina Rutherford 2011 vegetation dataset) to create highly accurate ecological niche models for the 10 threatened waterbirds in MaxEnt.

Objective 2: Using Arcmap 10.3 to assess the condition of the South African landscape based on the 2013/14 DEA landcover.

Objective 3: Using Marxan to assess whether the current the existing IBA network adequately protects the 10 threatened waterbird species and if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 4: Using Marxan to assess whether the current the existing protected area network adequately protects the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 5: Using Marxan to assess whether the existing PAN (Protected Area Network) adequately protects the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 6: Using Marxan to design a reserve network from conception that adequately protects the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 7: Using Marxan to expand on the existing PAN in order to adequately protect the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 8: To assess which reserve network design adequately protects all of the 10 threatened waterbird species best and aligns the most with the CARE principles of Systematic Conservation Planning.

2.5 Hypotheses

Hypothesis 1: The humidity bioclimatic variables would have higher percentage predictive contribution, as the ecology of waterbirds is more dependent on humidity as opposed to temperature and vegetation, therefore the distribution of waterbirds is related to the availability of water and wetlands in SA.

Hypothesis 2: A reserve network designed from conception by Marxan would be more spatial efficient and would more adequately protect all 10 waterbirds and contain all the reserve network good practice "CARE" principles than the IBA and current protected area networks. Additionally, a reserve network designed from conception by Marxan would complement the existing IBA and protected area networks.

2.6 Predictions

Prediction 1: Rainfall (In this case, humidity) is the strongest predictor of waterbird distributions and, subsequently, that waterbirds will tend to be found more in the wetter or more humid, eastern portion of the country, compared to the more arid western portion. Also, MaxEnt will generate highly accurate ecological niche models for all 10 threatened waterbirds with AUC values above 0.7.

Prediction 2: The current PANs are spatially efficient and adequately protect the 10 threatened waterbirds.

Prediction 3: A Marxan reserve design approach would adequately protect all 10 threatened waterbirds more efficiently than the IBA and current protected area networks.

Prediction 4: A reserve system designed by Marxan is not solely the best reserve network for the protection of the 10 threatened waterbirds by itself but instead its planning units could complement the existing IBA and protected area networks.

2.7 Software

The following software packages were used:

- ARCGIS 10.3 (http://desktop.arcgis.com/en/arcmap)(Esri 2011)
- Marxan version 2.4.3 (Ball et al. 2013 http://Marxan.net)
- MaxEntversion 3.3.4 (Phillips et al. 2006) https://biodiversityinformatics.amnh.org/open_source/MaxEnt

3 Evaluation of the use of the Ecological Niche Models to assess the effectiveness of a Protected Area Network

Abstract

Conservation planning often requires detailed data on species distribution (Margules and Pressey 2000). Taxonomic atlases or digital range maps are often used, however these datasets are too coarse and overestimate species occurences (Leme*set al*. 2011). Ecological Niche Models (ENMs) estimate species occurences at a finer scale which is used for conservation planning analyses (Leme*set al*. 2011).The MaxEnt software package is an ecological niche modelling programme that uses presence-only species distribution and environmental variables across a gridded user-defined landscape. After preparing the waterbird csv (comma separated values) sample records, humidity and temperature bioclimatic variables, and vegetation biome data were used as the environmental variables. Waterbirds rely on a combination of these environmental variables for their distribution ecology in their wetland habitat.A strong correlation coefficient of 0.9021 exists between humidity and precipitation, making humidity a suitable environmental variable for the ecological niche modelling of waterbirds. After running these data in MaxEnt, all of these models had a high degree of accuracy, as each of them had an Area Under the receiver-operating Curve (AUC) value of above 0.7. Most waterbirds had high predicted occurrence percentage values in provinces such as KwaZulu-Natal, Eastern Cape, Mpumalanga and Limpopo. Humidity and vegetation environmental variables were generally stronger predictor variables compared to temperature variables for predicted sites of suitability for waterbirds. However, temperature variables such as temperature seasonality and the minimum temperature of the coldest month had large percent contributions for waterbirds such as the African Marsh Harrier, Great White Pelican, Grey Crowned Crane and Wattled Crane as well. Due to insufficient sample records, MaxEntwas unable to be run for the White Winged Flufftail.The Merraclim dataset was used instead of the Worldclim dataset, since this dataset was released more recently (Vega et al. 2017). However, the Worldclim dataset containing the precipitation bioclimatic variables would have been a more suitable dataset to use for the waterbird species distribution modelling, since precipitation relates more directly to the ecology of these waterbirds.

Being wetland-dependent species, waterbird distribution and ecology is more directly dependent on precipitation compared to temperature (Rendon et al. 2008). Precipitation and humidity are, however, related to one another (Frei et al. 1998; Dessler and Sherwood 2000). According to Umoh et al. 2013, there is a correlation co-efficient of 0.9021 between humidity and precipitation. Humidity is the water vapour stored in the air before the atmosphere expresses it as precipitation, as a result of the pressure build-up in the atmosphere (Frei et al. 1998). The humidity variables provided and released by MERRACLIM in 2010 were a more recent dataset compared to precipitation variables provided and released by Worldclim in 2000 (Vega et al. 2017). As such, the humidity environmental variables from MERRACLIM were a suitable choice for the SDMs for the 10 waterbirds in this thesis. In this thesis, it was found that vegetation and humidity variables had the highest predictive powers and therefore would be considered more fundamental towards the distribution ecology of these waterbirds.

3.1 Introduction

The theory of climate change having a strong influence on plant and animal species distribution was first mentioned in literature around the first century BCE (Woodward 1988). However, it was only in the 1980s that reliable methods for estimating mean climatic conditions for any location were developed (Booth et al. 2014). This allowed plant and animal species distributions to be analysed from an explicitly quantitative basis for the first time (Booth et al. 2014). Various names have been given to this study of species distribution, including bioclimatic envelope, species niche and habitat suitability modelling. However, in this thesis, these models are referred to as Species Distribution Models (SDMs) (Franklin et al. 2015). How SDM software packages generally work is by the software assimilatinggeocoded information on species distribution and environmental variables under current or future scenarios in geographic space (Franklin et al. 2015). Due to its usefulness in the field of applied ecology such as invasive species management and conservation planning, there has been a rapid increase in the use of species distribution and ecological niche modelling in recent years (Peterson et al. 2011).

One of the first software packages developed for SDMs is a software package called Bioclim (Elith et al. 2011). Compared to more recent species distribution modelling packages like MaxEnt, Bioclim offers a more basic approach to species distribution modelling (Elith et al. 2011). When Bioclim was first developed, its use of simple ranges of environmental variables within an n-dimensional space was an approach that was closely related to the current understanding of ecological theory at that time (Booth et al. 2014). The understanding of species relationships to the environment then was that a niche was an n-dimensional hypervolume (Booth et al. 2014). In this hypervolume, the dimensions are environmental conditions and resources that define the requirements of a population of species to persist (Booth et al. 2014). A limitation of Bioclim was its inability to show which particular environmental conditions within a species range would be the most suitable (Elith et al. 2011). Also, Bioclim describes the n-dimensional hyperspace in terms of simple ranges (Elith et al. 2011). MaxEnt is more explicit in its ecological niche modelling outputs, since it develops a response curve for each of its environmental conditions, showing which specific conditions within a species range are more suitable (Booth et al. 2014). The development of Bioclim was, however, pivotal to the development and advancement of more advanced software such as MaxEnt in the area of ecological research (Peterson et al. 2011). For more than 20 years, it was the preferred used method in applied ecology and it continues to influence the advancement of current SDM work (Booth et al. 2014).

In the last two decades, there has been much advancement in the field of species distribution modelling and the methods for the species data used (Elith et al. 2011). One of the most common ways that species data have been collected is by systematically surveying sites in formal biological surveys to record the presence and absence of a species per site (Franklin 2015). The disadvantage of systematic biological surveys is that species distribution data tend to be sparse and limited in coverage (Booth et al. 2014). Presence-only species records are in herbarium and museum databases (Elith et al. 2011). Many of these databases have become an important source of species occurrence data as private and public sectors have invested nearly over a century in these databases (Booth et al. 2014). Due to the convenience of having such an abundant database available, an array of SDM methods for modelling presence-only data has been formulated (Peterson et al. 2011).

The MaxEnt software package is an ecological niche modelling programme that uses presence-only species distribution and environmental variables across a gridded user-defined landscape (Phillips et al. 2006). The main assumption of the input presence-only data is that they are randomly sampled records (Phillips et al. 2006). MaxEnt assesses the density of predictor variables at the presence sites and compares this to the density of predictor variables at the background locations (Dudik et al. 2005). The presence sites are those areas where species are known to occur (Phillips and Dudik 2008). The background sites are those sites that contain no sampled species records (Phillips and Dudik 2008). Using background data gives the model information about the density of environmental variables in the study area and provides the foundation for comparison with the density of environmental variables occupied by the species (Elith et al. 2011). After comparing the known and unknown sites of species occurrences, MaxEnt creates an ecological niche model (Phillips et al. 2006). When creating the ecological niche model, MaxEnt uses constraints on the solution in order for the result to reflect information from the presence records only (Elith et al. 2011). For example, if one environmental variable is summer rainfall, the constraints will ensure that the mean summer rainfall for MaxEnt's estimate is close to its mean across the locations with observed presences (Elith et al. 2011). The species distribution is thus estimated minimizing the distance (or maximizing the entropy) between the conditional density of the environmental variables at the present sites (undefined) and the unconditional density of environmental variables across the study area (undefined), subject to constraining the mean of each environmental variable close to the mean across presence locations (Elith et al. 2011). Using this, MaxEnt then generates a probability of pixel distributions across the defined geographic space which is referred to as an ecological niche model (Elith et al. 2011). This ecological niche model contains all the areas of sampled and unsampled species records with assigned probabilities of occurrence (Phillips et al. 2006). The more similar the niches are between the sampled and unsampled areas, the higher the probability of species occurrence (Phillips and Dudik 2008). A lower similarity between the sampled and unsampled areas will result in an area containing a lower probability of species occurrence (Phillips and Dudik 2008).

3.2Aim:

To determineand map the distribution of threatened waterbirds in South Africa using species distribution modelling techniques.

3.3 Research question

What is the distribution of threatened waterbirds in South Africa?

3.4 Objective

Use known locations and environmental predictors (MERRAclim Bioclimatic variables (1- 19) and Mucina Rutherford 2011 vegetation dataset) to create highly accurate ecological niche models for the 10 threatened waterbirds in MaxEnt.

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The humidity bioclimatic variables would have higher percentage predictive contribution, as the ecology of waterbirds is more dependent on humidity as opposed to temperature and vegetation, therefore the distribution of waterbirds is related to the availability of water and wetlands in SA.

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Rainfall (In this case, humidity) is the strongest predictor of waterbird distributions and, subsequently, that waterbirds will tend to be found more in the wetter or more humid, eastern portion of the country, compared to the more arid western portion. Also, MaxEnt will generate highly accurate ecological niche models for all 10 threatened waterbirds with AUC values above 0.7.

3.7. Input data

3.7.1 Selected Waterbird species

Ascriteria for inclusion in the study, waterbirds had to be threatened as perthe IUCN designation, use freshwater wetland as their habitat and have a threatened status on the BLSA 2018 Red List (Taylor et al. 2015). A total of eleven threatened freshwater wetland-dependent waterbirds were selected from the BLSA 2018 Red List (See Table 1). The justification for choosing the conservation features is shown inTable 3.

The following 11 waterbird species were selected for this analysis:

Table 1: The eleven threatened freshwater wetland-dependent waterbirds selected from the BLSA 2018 Red List

African Marsh Harrier	
 **Figure 1: Image of an African Marsh Harrier (hbw.com, 2014)**	The African Marsh Harrier (*Circus ranivorus*) (Figure 1) depends on wetlands, dry floodplains, grasslands and croplands as habitat (Simmons 2005). Landcover categories such as Fynbos and agriculture fields are used to build nests (Simmons 2005). The threats faced by this species include pollution and loss of wetland habitat caused by drainage and damming for development and agriculture (Curtis et al. 2004). This species depends on moist wetland edges with surrounding grasslands which they use for foraging prey (Simmons 2005). The decrease in

area outside of existing conservation networks for this species is of concern (Curtis et al. 2004). This species has not been included in any national management plans, but has been included into provincial management plans (Taylor et al. 2015). This species is listed as Endangered (Table 2). See Figure 12 for this species' spatial distribution.

African Pygmy Goose

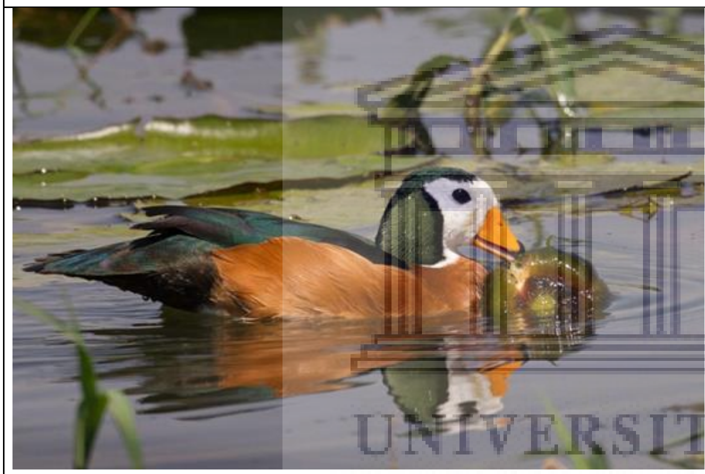


Figure 2: Image of an African Pygmy Goose (hbw.com, 2014)

The African Pygmy Goose (Figure 2) (*Nettapus auritus*) relies on still, clear, seasonal or permanent waterbodies such as wetlands, floodplains and pans in North Eastern KwaZulu-Natal (Tarboton 2001). This species' dependence on freshwater habitats is the reason it was included in future conservation plans (Harrison et al. 1997). *Papyrus* and old hamerkop (*Scopus umbretta)* are important vegetation used by this species for building nests (Tarboton 2001). Wetland degradation, destruction and interference with floodplain ecology are the major threats that this species faces e.g. Pongolapoort Dam (Taylor et al. 2005). This species is listed as Vulnerable (Table 2). See Figure 12 for this species' spatial distribution.

Black Stork

Figure 3: Image of Black Stork birds (hbw.com, 2015)

The Black Stork (Figure 3) is well represented in IBAs, occurring in over 40 IBA's globally (Taylor et al. 2005). It is absent from seasonal pans lacking fish (Allan 1997) but is found in dams, shallow pans and floodplains (Chevallier et al. 2008). It forages on shallow waterbodies like lakes and rivers (Chevallier et al. 2008). The degradation of wetlands and damming of small rivers have had negative impact on this species (Chevallier et al. 2008). The Black Stork is also prone to collision with powerlines at commercial fish farms (Taylor et al. 2005). It is placed in the fourth schedule: Specially protected of the KwaZulu-Natal Nature Conservation Management Amendment Act No.5 of 1999 (Taylor et al. 2005). The Black Stork is listed as Vulnerable (Table 2). See Figure 12 for this species' spatial distribution.

Great White Pelican

Figure 4: Image of a Great White Pelican (hbw.com, 2010)

The breeding distribution of the Great White Pelican (Figure 4) occurs in three localities, namely, Vondeling and Dassen Islands in Western Cape and Lake St. Lucia in KwaZulu-Natal (Taylor et al.2015). All three of these sites are IBAs (Taylor et al. 2015). Non-breeding birds can be found at large waterbodies in all other provinces (Williams and Borello 1997a). All breeding sites, however, have some form of protection (Taylor et al. 2015). iSimangaliso Wetland Park (a World Heritage Site and Ramsar Site) and Dassen and Vondeling Islands (World Heritage Sites), have benefited the species greatly by ensuring the protection of several important breeding sites (Williams and Borello 1997a). It has been recommended that biodiversity management should incorporate monitoring results from places like St. Lucia catchment, which is an important feeding and breeding site for this species, into future conservation plans (Mwema et al. 2010). This species is listed as Vulnerable (Table 2). See Figure 12 for this species' spatial distribution.

Grey Crowned Crane:

Figure 5: Image of a Grey Crowned Crane (hbw.com, 2014)

The Grey Crowned Crane (Figure 5) uses mixed wetland-grassland habitats (Filmer and Haultshausen 1992). It nests and feeds in wetlands, grasslands and croplands as well (Morrison and Bothma 1998). This species forages in open grasslands, lightly wooded savannah and agricultural fields (Pomeroy 1980). Cultivated lands are crucial habitats for the Great Crowned Crane, with 56% of this species' records having been recorded in cultivated lands (van Niekerk 2011). The main threat faced by the Great Crowned Crane is the degradation and loss of breeding habitat caused by draining and damming of wetlands (McCann et al. 2001a). In future, open-cast coal mining will pose a threat to available grassland habitats in Mpumalanga (McCann et al. 2001b). The inclination of the Great Crowned Crane to roost on powerlines, poses electrocution and collision threats to this species (Martin and Shaw 2010). EWTs African

	Crane Conservation Programme has field officers covering Mpumalanga and KwaZulu-Natal areas (Martin and Shaw 2010). EWTs Wildlife and Energy programme works with Eskom to reduce powerline collisions and electrocutions (Taylor et al. 2015). The Endangered Wildlife Trusts African Crane Conservation Programme has appointed officers to monitor and suggest key sites for the National Biodiversity Stewardship programme (Taylor et al. 2015). The Grey Crowned Crane is listed as Vulnerable (Table 2). See Figure 12 for this species' spatial distribution.
Lesser Jacana:	
 **Figure 6: Image of a Lesser Jacana (hbw.com, 2016)**	The Lesser Jacana (Figure 6) breeds only in northern KwaZulu-Natal (Tarboton 2001). It has vagrancy records from the Mpumalanga Highveld, Hwange Panveld and Zimbabwe (Tarboton and Fry 1986). It has been recorded in eight IBAs (Tarboton and Fry 1986). The Lesser Jacana occurs in shallow waters, around edges of seasonal or permanently flooded wetlands and areas of sparse sedges (del Hoyo et al. 1996). This species is an unpredictable monogamous breeder (Tarboton 2001). It breeds where there is sufficient grass or sedge cover (Tarboton 2001). Threats to this species include wetland degradation and destruction of floodplain ecology caused by dam construction and poor catchment management (Taylor 2015). Agricultural conversion, afforestation, and

	industrialization are the causes of habitat loss (Taylor 2015). Proper catchment management that feed the complex systems of wetland habitat for the Lesser Jacana is key for the conservation of this species (Coverdale and Theron 2015). It has been considered protected in terms of the provincial legislation (Coverdale and Theron 2015). The Lesser Jacana is listed as Vulnerable (Table 2). See Figure 12 for this species’ spatial distribution.
Pink Backed Pelican:	
 **Figure 7: Image of a Pink Backed Pelican (hbw.com, 2015)**	The Pink Backed Pelican (Figure 7) migrates within southern Africa from Nsumo and Nyamithi pans in summer to Lake St Lucia in winter (Bowker et al. 2010). The movements of this species have been recorded from Kwa Zulu-Natal moving into Mozambique (Bowker et al. 2010). These birds have also been recorded moving from the Caprivi and Okavango area into Northern Cape, North West and Gauteng Provinces (Williams and Borello 1997b). This species forages in both fresh and saline wetland types, including bays, lagoons, estuaries, lakes, dams and rivers (Williams and Borello 1997b). The main threat faced by the Pink Backed Pelican species is changes in natural flooding regimes of pans in the Pongola River Floodplain (Bowker et al. 2010). This species is listed as Vulnerable (Table 2). See Figure 12 for this species’ spatial distribution.

Saddle Billed Stork:

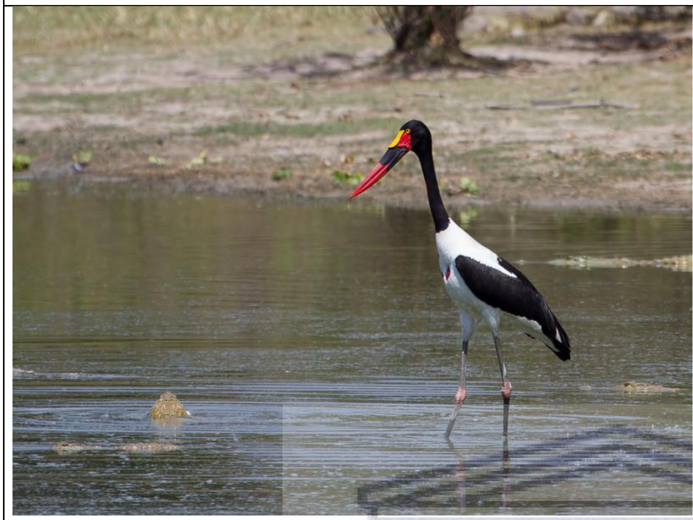


Figure 8: Image of a Saddle Billed Stork (hbw.com, 2012)

The Saddle Billed Stork (Figure 8) occurs in large perennial rivers and other waterbodies (Harrison et al.1997). The Kruger National Park, iSimangaliso Wetland Park, Mkuze Game Reserve and Hluhluwe-iMfolozi Park, all of which are IBAs, form the core of this species' range (Botha 2010). The Saddle Billed Stork is also found along the Limpopo River (Botha 2010). This bird occurs in aquatic habitats, large and small rivers, floodplains, wetlands and pans (Botha 2010). This bird's nomadic movement patterns is a response to drought conditions and feeding opportunities (Harrison et al.1997). This species feeds in open water or amongst flooded vegetation (Birdlife International 2014). It breeds in trees away from water (Birdlife International 2014). Habitat loss caused by water extraction and pollution events for the construction of urban settlements, agricultural fields and mining plants, is the main threat faced by this species (Taylor et al. 2005). The Saddle Billed Stork is listed under Schedule 2 of the Limpopo Environmental Management Act No.7 of 2003 (Botha 2010). This species is listed as Endangered (Table 2). See Figure 12 for this species' spatial distribution.

Wattled Crane:

Figure 9: Image of a Wattled Crane (hbw.com, 2012)

In former years, the Wattled Crane's (Figure 9) range was widespread, but is now confined to Eastern grasslands of South Africa, with the main population occurring in the Kwa Zulu-Natal Midlands (Smith 2015). A few pairs are found in the grasslands of Northern-Eastern Cape and the Highveld grasslands of Mpumalanga and Eastern Free State (McCann et al. 2001a). There is no evidence of movement in and out of the region and is therefore considered a single sub-population of the African population (McCann 2001b). These birds' breeding territories are found in permanently flooded wetlands (Meine and Archibald 1996). The main threat to this species is loss and degradation of permanent and inland wetlands caused by dam construction, afforestation and agricultural activity (McCann et al. 2000). Grasslands surrounding the wetlands are important for foraging and cover for this species' chicks (McCann et al. 2000). Another threat is that several powerline collisions have been reported between roosting and foraging sites (Smallie 2011). Current conservation efforts have been put in place by Ezemvelo Kwa Zulu-Natal Wildlife to protect its habitats (Taylor et al.2015). Kwa Zulu-Natal Crane Foundation encourages sustainable land-use practices by raising awareness with land owners (Smith 2015). The Endangered Wildlife Trust has suggested key areas of value to the Biodiversity Stewardship Programme (Taylor et al.2015). The Wildlands Conservation Trust has purchased several crane and wetland habitat as well (Taylor et al.2015).

	In 2000, Eskom and the Endangered Wildlife Trust have marked powerlines that are close to nests (Taylor et al.2015; Morrison and Bothma 1998). Securing important feeding and breeding habitats for the Biodiversity Stewardship agreements are strongly recommended (Morrison and Bothma 1998).There have been numerous crane conservation efforts since the 1980's (Morrison and Bothma 1998). This Wattled Crane is listed as Critically Endangered (Table 2). See Figure 12 for this species' spatial distribution.
White Winged Flufftail:	
 **Figure 10: Image of a White Winged Flufftail (hbw.com, 2014)**	Since 1995, the White Winged Flufftail(Figure 10) has been recorded at two sites in Kwa Zulu-Natal, four sites in North-Eastern Free State, and two sites in eastern Mpumalanga (Taylor et al. 2015). The area of occupancy for this species is estimated to be < 10 km² (Taylor et al. 2015). None of the sites in which the bird has been recorded are formally protected under the provincial or national legislation (Davies et al. 2015). This species occurs in permanent marshes dominated by dense sedges, mainly *Carex* sp. (Davies et al. 2015). The main threat to this species is the loss and reduction in quality of their wetland habitat (Davies et al. 2015). This has been caused by mining and agricultural activities, commercial plantations of exotic trees, erosion caused by overgrazing, construction of dams and drainage of wetlands (de Smidt 2003). Birdlife South Africa is involved

	at Ingula and advises Eskom construction activities to avoid adversely affecting their habitat (Taylor et al. 2015). Today, Ingula is a nature reserve (BirdLife South Africa 2020). Ezemvelo Kwa Zulu-Natal has developed a habitat suitability model for the White Winged Flufftail distribution to identify sites where this species occurs and sites to potentially conserve (Taylor et al. 2015). The South African White Winged Flufftail conservation plan was produced in 2005 and has not been reviewed or updated since (Taylor et al. 2015). Action plans for the White Winged Flufftail were compiled in 2003 (Davies et al. 2015). The White Winged Flufftail is listed as Critically Endangered (Table 2). See Figure 12 for this species' spatial distribution.
Yellow Billed Stork:	
 **Figure 11: Image of a Yellow Billed Stork (hbw.com, 2014)**	This species (Figure 11) has been described as nomadic (Taylor et al. 2015). It avoids arid western areas but is generally widespread in South Africa (Taylor et al. 2015). Breeding for this species occurs regularly at Nsumo Pan at Mkuze Game Reserve in KwaZulu-Natal (Bowker and Downs 2008). Isolated breeding records have been recorded in Engelhardt Dam, Kruger National Park and Nylsvley (Tarboton 2001). This Yellow Billed Stork forages in permanent and seasonal wetlands with open shallow water lacking vegetation (del Hoyo et al. 1996). The

	main threat to this species is loss of foraging wetland habitat such as pans, marshes and floodplains (Anderson 2005). No specific conservation measures are under way for the protection of the Yellow Billed Stork (Bowker et al. 2010). This species is listed as Endangered (Table 2). See Figure 12 for this species' spatial distribution.

Table 2: Thresholds for the Regional IUCN Red List Criteria (Taylor et al. 2015)

A. Population reduction (measured over 10 years or three generations)	**Critically Endangered (CR)**	**Endangered (EN)**	**Vulnerable (VU)**
A1	>90%	>70%	>50%
A2, A3 or A4	>80%	>50%	>30%
A1. Causes of reduction are reversible, understood and have ceased			
A2. Causes of reduction may not have ceased, reversible or be understood			
A3. Causes of reduction is expected to be met in future			
A4. Causes of reduction may not have ceased, be understood, or may not be reversible, based on A1			
B. Geographic range : either B1 (Extent occurrence) OR B2 (Area of occupancy)			
B1. Extent of occurrence	<100km²	<5000km²	<20000km²
B2. Area of Occupancy	<10km²	<500km²	<2000km²
and two of the following three criteria			
a. severely fragmented			
b. continuing decline			

c. Extreme fluctuations			
C. Small and declining population			
Number of mature individuals and either C1 or C2	<250	<2500	<10000
C1. A continuing decline of atleast up to 100 years	25% in 3 years	20% in 5 years	10% in 10 years
C2. A continuing decline and a or b			
a(i) Number of mature individuals in largest sub population	<50	<250	<1000
a(ii) Percentage of mature individuals in one sub population	90-100%	95-100%	100%
b. Extreme fluctuations in number of mature individuals			
D. Very small or restricted population			
(1): number of mature individuals	<50	<250	<1000
(2): Restricted area of occupancy	NA	NA	AoO<20km^2
E. Quantitative analysis			
Indicating probability of extinction in wild	50% in 10 years	<20% in 20 years	10% in 100 years

Table 3: Summary of justification for choosing the conservation features. Criteria pertain to population size, breeding range and species occurrence in protected areas.

Species name/species name	**Threat status**	**Population size and trend**	**Protection State**
African Marsh Harrier/*Circis*	Endangered.	There are < 2500 mature individuals, >50% decline over	No specific conservation measures are under way for the

ranivorus.		the past 24 year period and an estimated continual decline of > 20% in the next five years.	protection of this species.
African Pygmy Goose/*Nettapus auritus.*	Vulnerable.	There are < 2500 mature individuals. Its rate of decline has passed the 30% threshold.	Besides the establishment of iSimangaliso Wetland Park, no specific conservation measures are under way for the protection of this species.
Black Stork/*Ciconia nigra.*	Vulnerable.	There are < 1000 mature individuals. The population has been reduced by > 30% over a 47-year period.	No specific conservation measures are under way for the protection of this species.
Great White Pelican/*Pelecanus onocrotalus.*	Vulnerable.	The population consists of 2500 pairs restricted to < 5 breeding locations. > 5% of the global range occurs in South Africa. No population trend is available.	iSimangaliso Wetland Park and Dassen and Vondeling islands protect all this species breeding sites.
Grey Crowned Crane/*Balearica regulorum.*	Vulnerable.	There are < 3500 mature individuals left in the region. The regional population has decreased greater than 30 % over the past 45 years.	The EndangeredWildlife Trust, the Energy Programme, Eskom and International Crane Foundation have several conservation measures in place.
Lesser Jacana/*Microparra capensis.*	Vulnerable.	There are < 2000 mature individuals. There has been a < 10% decline in the regional population.	Besides the establishment of iSimangaliso Wetland Park, no specific conservation measures are under way for the protection of this species.
Pink Backed Pelican/*Pelecanus rufescens.*	Vulnerable.	The population is between 600 and 900 mature individuals. No population trend is available.	Breeding colonies are regularly monitored and is usually a subject of many research topics. Other than this, no conservation measures are underway.
Saddle Billed	Vulnerabl	The population is < 250	Most of this species range falls

Stork/*Ephippiorhynchus senegalensis.*	e.	mature individuals. No population trend is available.	within the Kruger National Park. This conservation area is well protected.
Wattled Crane/*Bugeranus carunculatus.*	Critically Endangered.	The population is < 250 mature individuals. No population trend is available.	Ezemvelo KwaZulu-Natal Wildlife, KwaZulu-Natal Crane Foundation and the Endangered Wildlife Trust have several conservation programmes in place for this species.
White Winged Flufftail/*Sarothrura ayresi.*	Critically Endangered.	The population size is < 50 mature individuals. No population trend is available.	Mpumalanga, the Middlepunt Wetland Trust, Birdlife South Africa, Eskom and Ezemvelo KwaZulu-Natal have several conservation measures in place.
Yellow Billed Stork/*Mycteria ibis.*	Endangered.	There are between 150 and 350mature individuals remaining. No population trend is available.	No specific conservation measures are under way for the protection of this species

3.7.2 South African Bird Atlas Project 2 (SABAP2 species) observation data

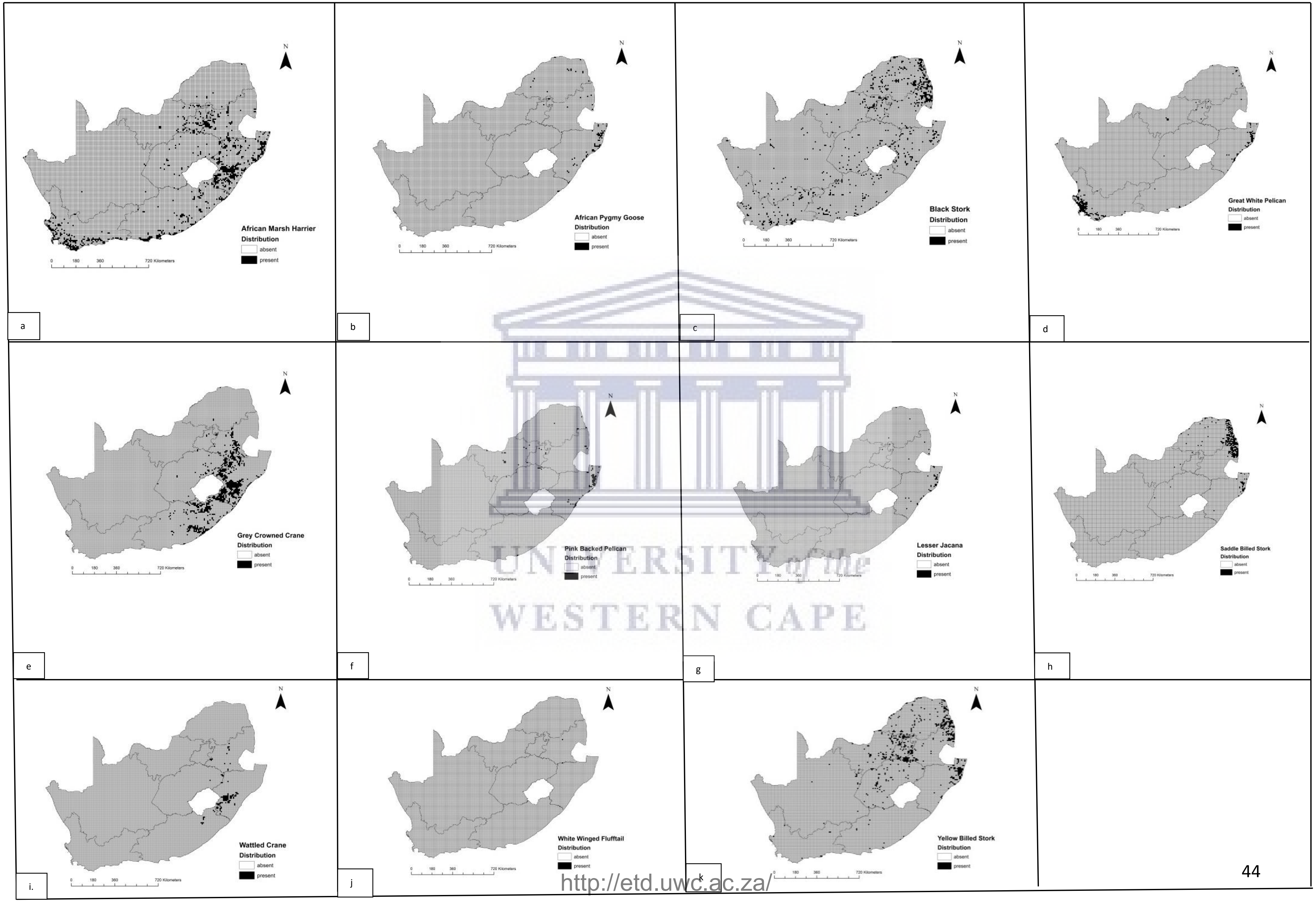
SABAP 1 was the first bird atlas project which lasted from 1987-1991. SABAP2, a partnership between the South African National Biodiversity Institute (SANBI), Animal Demographic Unit (ADU) and Birdlife South Africa, was instituted on 01 July 2007 and plans to run perpetually (Animal Demography Unit 2007). The project maps the distribution of relative abundance of all birds in South Africa, Lesotho and Swaziland (Animal Demography Unit 2007). Consequently, the second South African Bird Atlas (SABAP2) dataset started in 2007 and is the most recent and important bird conservation project in the region. Compared to the quarter degree grid (23kmx 27km) cells used in SABAP1, the pentads (5 x 5 minutes) are at a finer scale resolution, making it a more accurate data source as they are smaller grid cells (Animal Demography Unit 2007). A total of 9 pentads make up one quarter degree grid cell (Animal Demography Unit 2007).

The field work for SABAP2 is carried out by more than 1900 volunteers (Animal Demography Unit 2007). The observation-based data is collected in units called pentads (Animal Demography Unit

2007). Each pentad is surveyed for a minimum of two hours in as much habitats as possible (Animal Demography Unit 2007). This is known as the initial intensive survey. Species are recorded in the order in which they are heard or seen (Animal Demography Unit 2007). The maximum survey period for any one pentad is five days (Animal Demography Unit 2007). This allows for gauging what the most common species are in the pentad (Animal Demography Unit 2007). It is recommended for volunteers to do the initial intensive survey on day one of the five days (Animal Demography Unit 2007). Any new species is added (in the order that they were observed) to the list after the initial intensive survey, up until the end of the fifth day (Animal Demography Unit 2007).

A new survey for a pentad should only be started at the end of each five-day period (Animal Demography Unit 2007). All records are compared against multiple occurrence datasets with known range records before they are queried and verified for inclusion (Animal Demography Unit 2007). The SABAP2 dataset used for this analysis is from the period 01 July 2007 - 20 September 2017 (Animal Demography Unit 2007).

All SABAP2 species distribution data was downloaded from GBIF.org for the entire South Africa in csv format (Animal Demography Unit 2007). Each species was filtered, and then downloaded separately to make the analysis in excel more manageable (Animal Demography Unit 2007). The same SABAP2 data from the ADU were used (Animal Demography Unit 2007). Using the text import wizard, these csv files were imported into excel (Animal Demography Unit 2007). All unnecessary columns were deleted, as MaxEnt only requires the sample files to have the columns in the required x, y, z representing longitude, latitude and species respectively (Youngs et al. 2011). All semi colons were replaced with commas (Youngs et al. 2011). Some sample files had missing environmental data. In this case, those species sample records were removed as it resulted in inaccurate MaxEnt model outputs (Youngs et al. 2011).



a
African Marsh Harrier
Distribution
absent
present
0 180 360 720 Kilometers
N
b
African Pygmy Goose
Distribution
absent
present
0 180 360 720 Kilometers
N
c
Black Stork
Distribution
absent
present
0 180 360 720 Kilometers
N
d
Great White Pelican
Distribution
absent
present
0 180 360 720 Kilometers
N
e
Grey Crowned Crane
Distribution
absent
present
0 180 360 720 Kilometers
N
f
Pink Backed Pelican
Distribution
absent
present
0 180 360 720 Kilometers
N
g
Lesser Jacana
Distribution
absent
present
0 180 360 720 Kilometers
N
h
Saddle Billed Stork
Distribution
absent
present
0 180 360 720 Kilometers
N
i.
Wattled Crane
Distribution
absent
present
0 180 360 720 Kilometers
N
j
White Winged Flufftail
Distribution
absent
present
0 180 360 720 Kilometers
N
k
Yellow Billed Stork
Distribution
absent
present
0 180 360 720 Kilometers
N

Figure 12(a-k): Pentad distributions of the 11 waterbirds across South Africa

3.7.3 Environmental and vegetation variables

Mean temperature and humidity bioclimatic variables 1-19 (Table 5) for the year 2000-2010 at 2.5 minute resolution were downloaded. All TIF.format environmental variable layers were imported into ArcMap. All of this data had no projected format. The data was converted into WGS84 Albers equal area format (Table 4) for all MaxEnt operations in ArcMap. The extract by mask tool was used to clip the environmental variables so that it matched the extent (geographic bounds and cell size) of the study area. A shapefile of the boundary of South Africa was used as the feature mask datum. After clipping the first bioclimatic variable, it was used as the feature mask layer for the remaining bioclimatic variables. The environmental settings of the extract by mask tool were used to change the output co-ordinate system, processing extent and cell size of the remaining bioclimatic variables 2- 19 equivalent to match that of bioclimatic variable 1's format. The extent of the geographic boundaries used were: top: -22.1293949999, left: 16.4519099997, right: 32.9056349997, and bottom: -34.8341699999. The cell size used was X: 0.041655 and Y: 0.041655. The 19 bioclimatic and biome vegetation variables (see Table 5) were converted to ASCII format in ArcMap. ArcMap did not freeze when running biome types, it did freeze when running vegetation types. A computer with 4 gigs of RAM was used for the MaxEnt analysis. In future, good practice would possibly be to do this analysis on a computer with more than 4 gigs of RAM (Youngs et al. 2011). For this reason, biome vegetation variables were used. The ASCII format data was projected into the WGS84 datum before running in MaxEnt version 3.3.4. The version of MaxEnt used for this thesis was downloaded from https://biodiversityinformatics.amnh.org/open_source/MaxEnt/ (Phillips et al. 2018). The memory usage used on MaxEnt was 1024mb.

Table 4: Projected co-ordinate system used for the MaxEnt and Marxan analysis

Projected Coordinate System:	**Albers_24_18_32_GCSWGS.**
Projection:	Albers.
False_Easting:	0.
False_Northing:	0.
Central_Meridian:	24.
Standard_Parallel_1:	-18.

Standard_Parallel_2:	-32.
Latitude_Of_Origin:	0.
Linear Unit:	Meter.

Table 5: MaxEnt variable descriptions. These variables are a combination of inputs(defined by the user in MaxEnt) and outputs (results generated by MaxEnt).

Variable name	**Description**
Training data.	A random subset of the data selected by the user to train the data in order to fit the parameters of the species distribution model.
Test data.	A random subset of the data selected by the user to test or validate the performance of the species distribution model.
AUC.	Area under curve percentage value indicating the accuracy of the MaxEnt model (above 0.7 is accurate).
Average training AUC.	AUC for the training data.
Average test AUC.	AUC for the test data.
AUC standard deviation.	AUC standard deviation from mean for both training and test data.
Average percent contribution Jackknife training gain with only the variable.	Variables with high regularized training gain indicate how important a variable is when used in isolation.
Jackknife AUC with only the variable.	Variables with high regularized test gain indicate how important a variable is when used in isolation.
Response curves.	Shows the predicted probability of presence changes as each environmental variable is varied.
Average sensitivity vs 1-Specificity.	Sensitivity (True positive rate)versus 1-Specificity (False positive rate) is plotted byMaxEnt as omission vs commission error, from which the area under the curve (AUC), is calculated as a measure of model performance. The bootstrap of the AUC is also calculated as AUC standard error/deviation.

Environmental variable.	This covariate is represented across the user defined gridded landscape and used to determine the similarity of niches between sampled and unsampled records. Bioclimatic variables (1-19) and Biome vegetation data were used in this study.
Bio 1 (*10°C).	Annual Mean Temperature.
Bio 2 (*10°C).	Mean Diurnal Range or Mean of monthly (max temp - min temp).
Bio 3 (*10°C).	Isothermality (BIO2/BIO7) (* 100).
Bio 4 (*10°C).	Temperature Seasonality (standard deviation *100).
Bio 5 (*10°C).	Max Temperature of Warmest Month.
Bio 6 (*10°C).	Min Temperature of Coldest Month.
Bio 7 (*10°C).	Temperature Annual Range (BIO5-BIO6).
Bio 8 (*10°C).	Mean Temperature of Wettest Quarter.
Bio 9 (*10°C).	Mean Temperature of Driest Quarter.
Bio 10 (*10°C).	Mean Temperature of Warmest Quarter.
Bio 11 (*10°C).	Mean Temperature of Coldest Quarter.
Bio 12 (100000* kg of water/kg of air).	Annual MeanSpecific Humidity.
Bio 13 (100000* kg of water/kg of air).	Specific Humidity of most humid month.
Bio 14 (100000* kg of water/kg of air).	Specific Humidity of least humid month.
Bio 15 (100000* kg of water/kg of air).	Specific Humidity seasonality (Coefficient of Variation).
Bio 16 (100000* kg of water/kg of air).	Specific Humidity Mean of most humid quarter.
Bio 17 (100000* kg of water/kg of air).	Specific Humidity Mean of least humid quarter.
Bio 18 (100000*	Specific Humidity Mean of warmest quarter.

kg of water/kg of air).	
Bio 19 (100000* kg of water/kg of air).	Specific Humidity Mean of coldest quarter.
Vegetation Biome variables.	Fynbos, Azonal Vegetation, Forests, Waterbodies, Albany Thicket, Succulent Karoo, Nama Karoo, Grassland, Savannah, Desert and Indian Ocean Coastal Belt.

3.8 MaxEnt input files and settings

Bioclimatic variables 1-19 were classified as continuous variables and the biome environmental data were classified as categorical data. None of the environmental variables were tested for co-linearity before running MaxEnt. Ten replicates were set for each time MaxEnt was run per species. A random test percentage of 25% was used (See Table 6for samples sizes of each waterbird species). Selecting 25% as the random test percentage sets aside 25% of the sample records for testing (Phillips et al. 2006). The remaining 75% of the samples were then used as the training samples (Phillips et al. 2006). MaxEnt offers three options for replication, namely, cross-validation, subsampling and bootstrapping (Phillips et al. 2006). Setting the replicate run type to cross-validate was not appropriate as when this was used, the random test percentage was reset back to zero after running MaxEnt. The reason why MaxEnt did this, is unknown. Bootstrapping was also not used, since it samples with replacement, which results in duplicates in the training dataset (Wisz et al. 2008). The subsample was therefore chosen as the replicated run-type. The regularization multiplier was set to 1. This value of 1 was set without experimenting different values for the regularization multiplier and evaluating its effect of the AUC values. A random seed was specified, with 500 used as the maximum iterations. A bias file for each sample file was not used, while a logistic output was used. A logistic output is MaxEnt's attempt to get as close as possible to an estimate of the probability that the species is present, given the environmental variables (Phillips et al. 2006). When choosing a feature type run, the number of distribution points present per sample was determined. MaxEnt does not reliably model species with fewer than 10 records (Wisz et al. 2008). Since the White Winged Flufftail only had 2 sample records, it was removed from the analysis. The linear run type was used for species possessing less than 10 sample records, in this instance -the White Winged Flufftail, see Table 6. Some latitude and longitude points from sample records did not have any environmental data; these were removed before running MaxEnt. These missing values were not recorded after MaxEnt sent the "sample records containing no environmental data" pop-up notification.

3.9 Results

Figure 13 shows the Receiver Operating Characteristic (ROC) graphs, with the 0.5 line representing a random model (Phillips et al. 2006).The ROC values generated by MaxEnt are compared to the 0.5 value of a random model, in order to determine the accuracy of the model (Phillips et al. 2006). If the ROC value of the model is greater than 0.5, it means that it performed better than the random model and is an accurate model (Phillips et al. 2006). If the ROC value of the model is less than 0.5, it means that it performed worse than the random model and therefore is not an accurate model (Phillips et al. 2006).

For the 10 waterbird species, the Species Distribution Models (SDMs) generated by MaxEnt performed better than a random model (Phillips et al. 2006) (Figure 13). The AUC value of a random model is 0.5. As seen in Table 6, all of the SDMs had an average test and training AUC value above 0.7, meaning that all of these models had a high degree of accuracy (see appendix for the individual area under curve graphs for each species).

As seen in Table 5, the MaxEnt model uses both training and test data. In Table 5, the output AUC value for the model accuracy is therefore composed of both training and test data (Phillips et al. 2006). Figure 13 alsoshows the predicted occurrence maps (located on the right half of Figure 13). These maps show the predicted occurrence percentage for each species across the vegetation biomes.The predicted area of presence maps did not look very different from the observed point distribution occurrence maps for each species -see maps in the appendix showing observed data occurences. The predicted occurrence percentage values were categorized as being either low (0-30%), medium (30-50%) and high (50-100%) for each waterbird species.These thresholds were determined using the Technical guidelines for CBA Maps: Guidelines for developing a map ofCritical Biodiversity Areas & Ecological Support Areas using systematic biodiversity planning (Driver et al. 2017). According to these predicted occurrence percentage maps for each waterbird species, most waterbirds had high predicted occurrence percentage values in Eastern regions of South Africa, including provinces such as KwaZulu-Natal, Eastern Cape, Mpumalanga and Limpopo. Parts of the North-West, Free State and Western Cape Provinces had areas of high predictive occurrences as well. However, the North-West, Free State and Western Cape Provinces mostly contained areas of medium predicted occurrence percentage values.

The Northern Cape contained the largest amount of area with low predicted occurrence percentage values and the least amount of area with high predicted occurrence percentage values. Figure 13 therefore essentially shows that the predictive occurrence percentage values on the maps start to decrease in vegetation areas located in the western and inland regions, for example, the Northern Cape. Table 6 showed that the most accurate model generated by MaxEnt was for the Wattled Crane, having an average training and test AUC values of 0.9704 and 0.9696 respectively, with a standard deviation of 0.0063. Table 6 also showed that the least accurate model generated by MaxEnt was for the Black Stork, having a training and test AUC values of 0.7434 and 0.7376 respectively, with a standard deviation of 0.0185.

According to Table 7, certain temperature variables (*10°C) had high percentage predictive contributions towards certain waterbird species. Temperature seasonality, temperature annual range, minimum temperature of the coldest month, mean temperature of the wettest quarter, and mean temperature of the warmest quarter had high percentage predictive contribution values towards certain waterbird distributions such as the African Marsh Harrier, Great White Pelican and Wattled Crane. The average bioclimatic temperature percentage predictive contribution values overall ranged from 0.73 to 6.87, with Temperature Seasonality having the highest percentage predictive contribution of 6.87, and Mean of Monthly temperature having the lowest percentage predictive contribution of 0.73 (Table 7). According to the averages from Table 7, certain humidity variables (100000* kg of water/kg of air) had higher percentage predictive contributions towards certain waterbird species. Humidity variables such as Annual Mean Specific Humidity, Specific Humidity of Most Humid Month, Specific Humidity Mean of Most Humid Quarter and Specific Humidity Mean of Coldest Quarter were particular strong predictors of waterbirds distributions such as the African Pygmy Goose, Black Stork, Lesser Jacana, Saddle Billed Stork and Pink Backed Pelican. The average percentage predictive contribution overall ranged from 1.970 to 12.15, with Specific Humidity Mean of warmest quarter having the lowest percentage predictive contribution of 1.970 and Annual Mean Specific Humidity having the highest percentage predictive contribution of 12.15 (Table 7). With reference to this range difference and average percentage predictive contributions between the humidity and temperature variables, a comparisonbetween these two bioclimatic variables,clearly reveals that the humidity bioclimatic variables had a stronger variable contribution towards the distribution of waterbirds in this thesis compared to the temperature bioclimatic variables (Table 7). Table 7 shows that the vegetation biomes had the highest average percentage predictive contribution of 16.907 compared to any other environmental variables for the waterbird species. Annual Mean Specific Humidity was the environmental variable with the second highest average percentage predictive contribution 12.151 (Table 7). This information shows that the distributions of the 10 waterbirds (excluding the White Winged Flufftail) for this study are more strongly dependent on vegetation biome and humidity environmental variables as opposed to the temperature environmental variables.

Table 6: Average training and test AUC valuesas well as the Standard deviation for all ten waterbirds for each bioclimatic variable (1-19) and biome vegetation environmental variables.

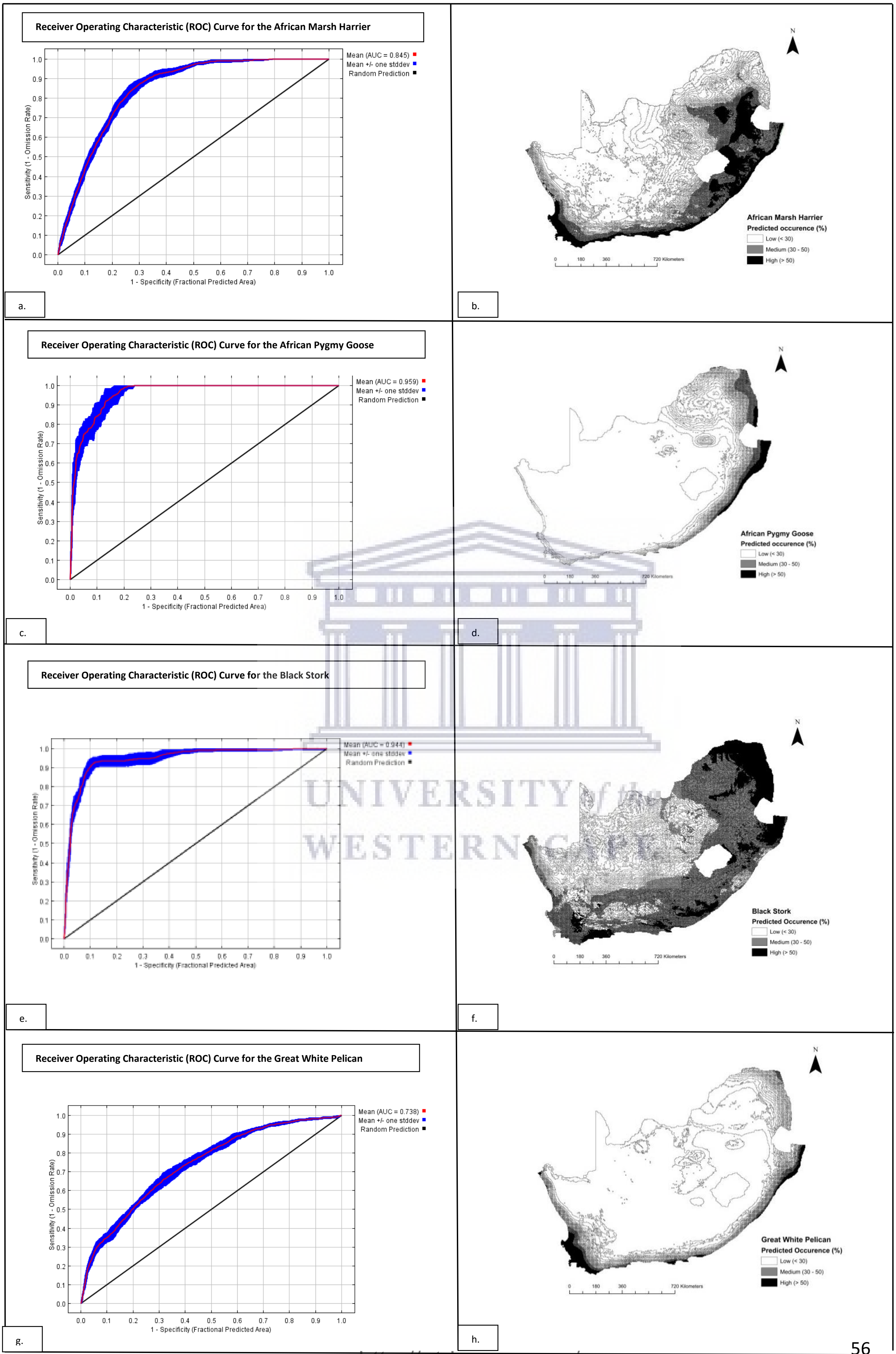
Species Name	No. of Observations	Average Training AUC	Average Test AUC	AUC Standard Deviation
African Marsh Harrier	866	0.851	0.845	0.010
African Pygmy	85	0.963	0.960	0.012

Goose				
Black Stork	713	0.743	0.738	0.019
Great White Pelican	242	0.950	0.944	0.014
Great crowned crane	743	0.902	0.899	0.007
Lesser Jacana	44	0.960	0.953	0.023
Saddle Billed Stork	98	0.962	0.963	0.007
Pink Backed Pelican	277	0.936	0.930	0.021
Wattled Crane	109	0.970	0.970	0.006
Yellow Billed Stork	576	0.866	0.855	0.014

Table 7: Percentage predictive contribution (%) of each individual environmental variable towards the predictive occurrence of each waterbird species.

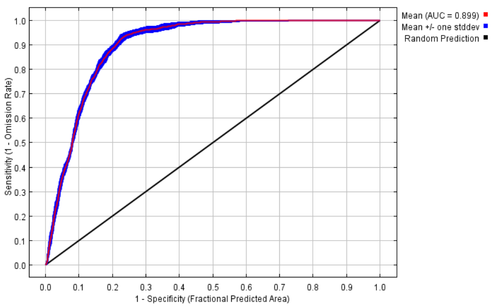
Model Variable	African Marsh Harrier	African Pygmy Goose	Black Stork	Great White Pelican	Great crowned crane	Lesser Jacana	Saddle Billed Stork	Pink Backed Pelican	Wattled Crane	Yellow Billed Stork	Average
Bio1_TemP_meanAnn	1.485	0.177	0.525	0.627	5.665	0.093	2.205	0.050	5.995	1.570	1.839
Bio2_Temp_MeanDRange	2.529	0.440	0.158	1.735	0.524	0.419	0.088	0.645	0.480	0.301	0.732
Bio3_Temp_Isotherm	1.347	2.881	**13.532**	1.533	3.033	0.022	**14.850**	2.924	1.872	4.787	4.678
Bio4_Temp_Season(STD*100)	**20.290**	0.234	7.975	5.236	**13.828**	1.649	0.796	2.366	8.297	8.065	6.874
Bio5_Max_Temp_Warmest_Mon	3.330	0.459	1.841	0.562	7.294	0.000	2.016	0.735	4.152	1.153	2.154
Bio6_Min_Temp_Coldest_Mon	2.358	1.244	2.096	**36.784**	0.918	3.246	3.984	1.819	3.044	8.595	6.409
Bio7_Temp_Ann_Ran_(BIO5-BIO6)	**8.367**	0.290	0.968	1.573	2.482	0.212	0.175	0.668	3.528	0.824	1.909
Bio8_Mean_Temp_Most_Hum_quart	1.530	0.479	0.602	1.282	5.603	0.000	1.536	1.607	**11.178**	1.726	2.554
Bio9_Mean_Temp_Least_Hum_Quart	1.218	1.081	4.278	0.645	2.594	0.727	5.489	0.898	1.936	1.387	2.025
Bio10_Mean_Temp_Most_Warm_Quart	2.525	0.409	0.534	1.506	**9.287**	0.074	0.966	0.616	**23.357**	2.342	4.161

Bio11_Mean_Temp_Coldest_Quart	0.327	1.294	1.877	0.845	1.811	0.555	2.953	0.825	1.124	1.683	1.329
Bio12_Ann_Mean_Spec_Hum	1.897	**32.707**	4.190	1.850	0.716	**58.491**	2.769	**15.469**	0.066	3.353	12.151
Bio13_Spec_Hum_Most_Hum_Mon	1.146	**9.387**	**15.449**	0.460	0.610	**6.175**	**21.065**	13.500	0.627	**25.823**	9.424
Bio14_Spec_Hum_Least_Hum_Mon	2.388	3.720	4.549	**8.557**	0.066	1.303	1.719	1.974	0.290	0.626	2.519
Bio15_Spec_Hum_Season_(Coef_of_Var)	1.145	2.088	6.795	1.435	3.099	1.604	9.449	1.748	5.431	**14.530**	4.732
Bio16_Spec_Hum_Mean_Most_Hum_Quart	1.141	**22.183**	**13.702**	0.287	1.219	**9.180**	**13.160**	**21.193**	0.620	7.524	9.021
Bio17_Spec_Hum_Mean_Least_Hum_Quart	1.517	7.974	3.109	7.181	0.187	4.457	3.269	9.200	0.668	1.444	3.901
Bio18_Spec_Hum_Mean_Warm_Quart	0.913	2.589	2.686	1.141	2.136	2.728	1.277	2.533	1.121	2.577	1.970
Bio19_Spec_Hum_Mean_Cold_Quart	3.433	7.225	2.614	6.030	0.424	5.669	1.999	**17.738**	0.694	1.282	4.711
Vegetation_Biome_Veg	**41.116**	3.138	12.520	**20.735**	**38.504**	3.398	10.235	3.494	**25.521**	**10.411**	16.907



Receiver Operating Characteristic (ROC) Curve for the African Marsh Harrier
Mean (AUC = 0.845)
Mean +/- one stddev
Random Prediction
Sensitivity (1 - Omission Rate)
1 - Specificity (Fractional Predicted Area)
a.
African Marsh Harrier
Predicted occurence (%)
Low (< 30)
Medium (30 - 50)
High (> 50)
720 Kilometers
b.
Receiver Operating Characteristic (ROC) Curve for the African Pygmy Goose
Mean (AUC = 0.959)
Mean +/- one stddev
Random Prediction
Sensitivity (1 - Omission Rate)
1 - Specificity (Fractional Predicted Area)
c.
African Pygmy Goose
Predicted occurence (%)
Low (< 30)
Medium (30 - 50)
High (> 50)
720 Kilometers
d.
Receiver Operating Characteristic (ROC) Curve for the Black Stork
Mean (AUC = 0.944)
Mean +/- one stddev
Random Prediction
Sensitivity (1 - Omission Rate)
1 - Specificity (Fractional Predicted Area)
e.
Black Stork
Predicted Occurence (%)
Low (< 30)
Medium (30 - 50)
High (> 50)
720 Kilometers
f.
Receiver Operating Characteristic (ROC) Curve for the Great White Pelican
Mean (AUC = 0.738)
Mean +/- one stddev
Random Prediction
Sensitivity (1 - Omission Rate)
1 - Specificity (Fractional Predicted Area)
g.
Great White Pelican
Predicted Occurence (%)
Low (< 30)
Medium (30 - 50)
High (> 50)
720 Kilometers
h.

Receiver Operating Characteristic (ROC) Curve for the Grey Crowned Crane



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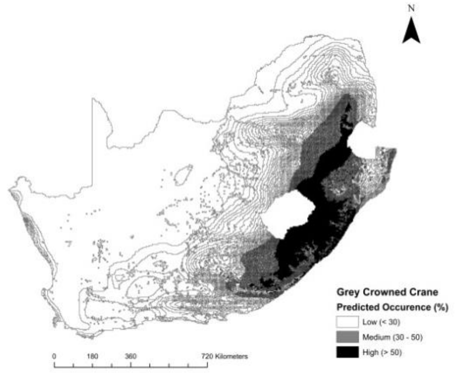
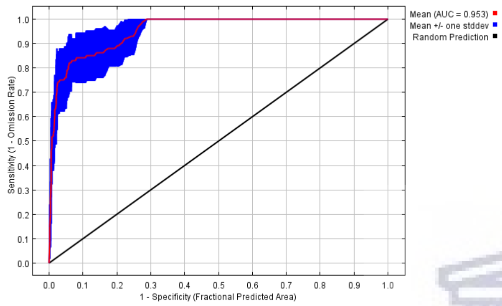


j.

Receiver Operating Characteristic (ROC) Curve for the Lesser Jacana



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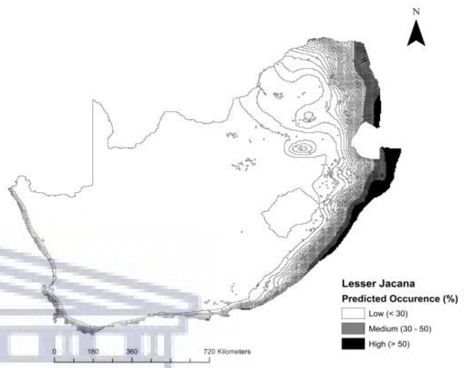
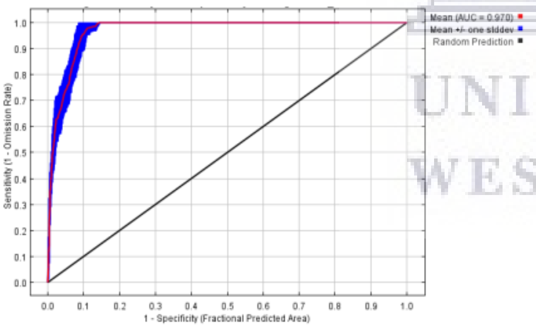


l.

Receiver Operating Characteristic (ROC) Curve for the Pink Backed Pelican



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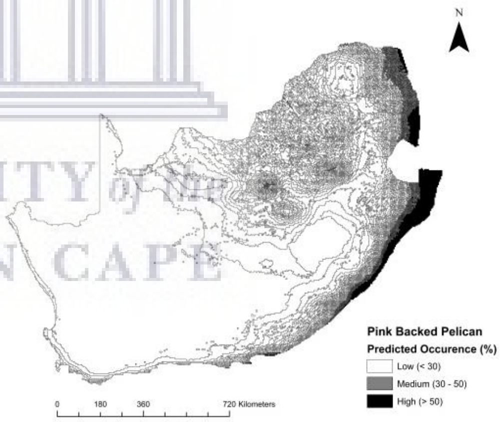

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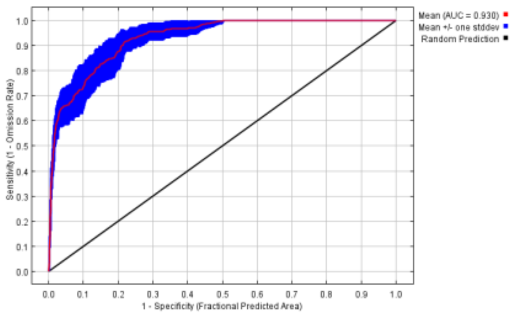
Receiver Operating Characteristic (ROC) Curve for the Saddle Billed Stork



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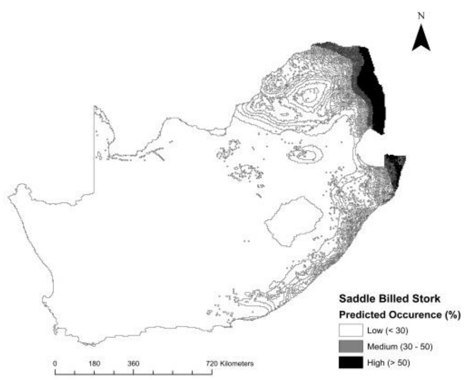

p.

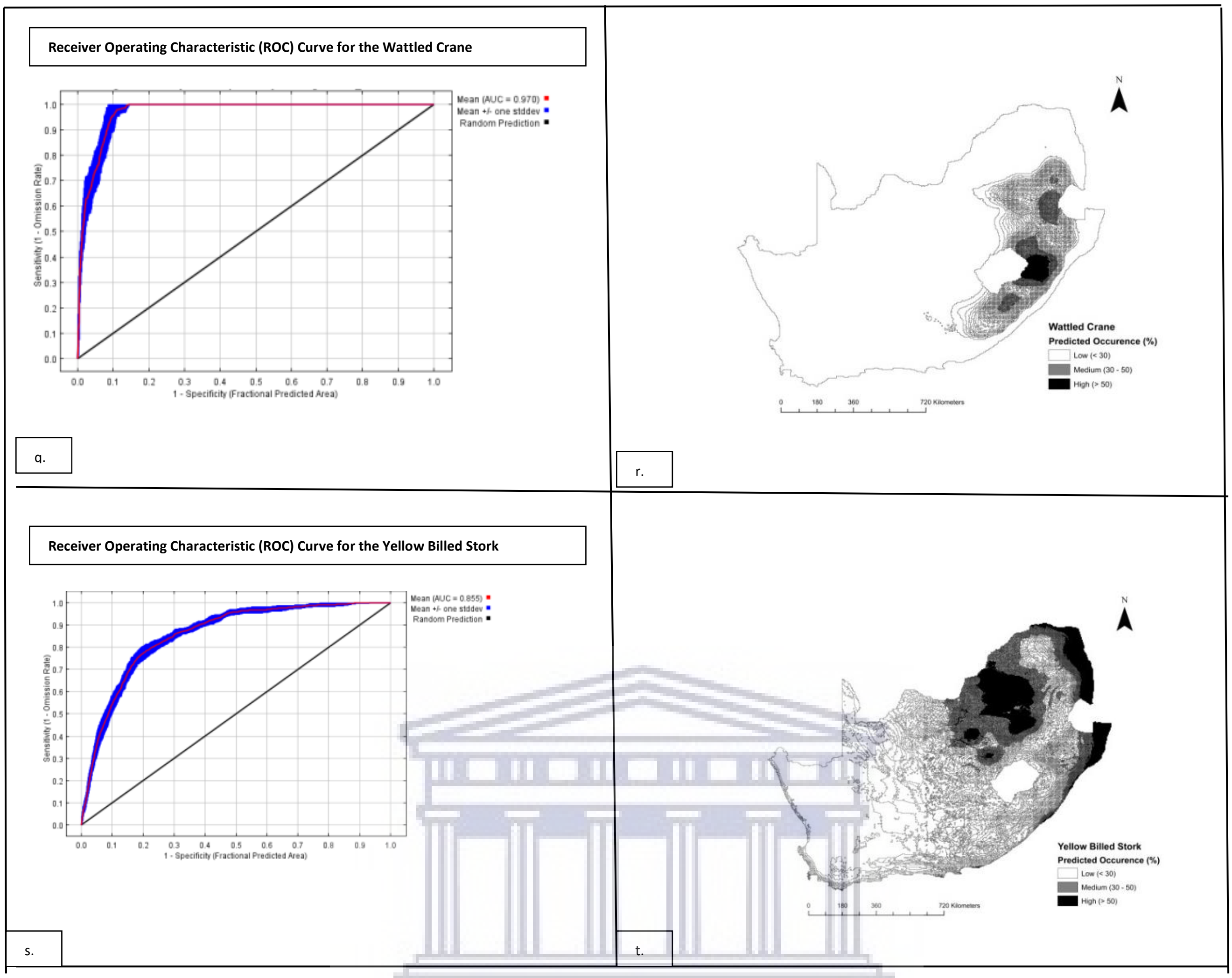

Figure 13(a-t): Receiving Operating Characteristic (ROC) curve that plots model sensitivity (true positive rate) versus 1-specificity (false positive rate), on the left and a map of MaxEnt's predicted of occurrence (%) on the right for all ten waterbirds. For the ROC curves, the Mean AUC is the average Area under the curve, represented as a probability, showing how accurate the MaxEnt model was, with a value of 1 being most accurate and a value of 0 being least accurate. One stddev represents the standard deviation value of the AUC, within 1 standard deviation of the mean. Random prediction is the random model generated by MaxEnt measured at a probability of 0.5.

3.10 Discussion

The research question and aim of this study was achieved by mapping the distribution of threatened waterbirds in South Africa using species distribution modelling techniques.It was predicted thathumidity is the strongest predictor of waterbird distributions and that waterbirds will tend to be found more in the wetter or more humid, eastern portion of the country, compared to the more arid western portion.However, in this study, the vegetation biome variables had the highest average percentage predictive contribution for all of the waterbirds distributions compared to all of the other average variable percentage predictive contributions. Vegetation cover is used by different waterbird species in various ways (O'Neal et al. 2008). For example, some waterbirds use vegetation directly as a food source by consuming seeds, leaves, tubers and rhizomes, while other species rely on sufficient vegetation cover for their breeding (Zhu and Zou 2001). Wetland vegetation cover influences the distribution of most wetland bird guilds (O'Neal et al. 2008). Greater densities of waterbird populations are located in wetlands with vegetation as opposed to landcovers consisting solely of either vegetation or open water (O'Neal et al. 2008). The hypothesis was therefore rejected since the vegetation biome variables had the highest average percentage predictive contribution to the 10 waterbirds distributions as opposed to humidity environmental variables.The vegetation data used was coarser than the bioclimatic data.This could be why the vegetation dataset had a higher average percentage predictive contribution compared to humidity. The scale of data affected the predictive accuracy of the MaxEnt model (Kumar et al.2014). Therefore, using more fine scale vegetation data, such as individual vegetation biome data, might have made the predictive contribution lower than humidity and essentially more accurate (Kumar et al.2014).

Although the hypothesis was rejected, the annual mean specific humidity, which was one of the 8 humidity variables, had the second highest average percentage predictive contribution for the 10 waterbird distributions. The results show that between the two bioclimatic variables, namely temperature and humidity, humidity on average had a higher percentage predictive contribution for the 10 waterbirds compared to that for temperature. Wetland-dependent waterbird species rely on precipitation events (or humidity variables used in this study), through various phases of their lifecycle and for their breeding and feeding ecology (Taylor et al. 2015). As noted in the results, the southern and eastern provinces of South Africa contained the greatest area with high predicted percentage occurrence values. The western and northern regions contained the greatest area with the lowest predicted percentage occurrence values. Most waterbird species tend to avoid the dry western and interior regions of South Africa such as the Northern Cape (Siegfried 1967). The Black

Stork is an example of a waterbird that regularly avoids these dry interior regions which do not contain the suitable wetland habitat for waterbird ecology (Siegfried 1967).

The objective of this study was successfully pursued in that MaxEnt generated highly accurate ecological niche models for the ten threatened waterbirds with AUC values above 0.7. The use of presence-only data in MaxEnt allows many complications associated with presence-absence analytical methods to be avoided (Peterson et al. 2005). MaxEnt's insensitivity to spatially correlated variables, (which often occurs when using multiple climate variables), allows highly accurate SDMs with high AUC values to be generated (Phillips et al. 2004; Merow et al. 2013). A study done by Reside et al. 2012, also generated accurate bird SDMs with AUC values above 0.7, using MaxEnt software with multiple environmental variables. Since all the MaxEnt ecological niche models for all of the ten waterbirds in this thesis were highly accurate, the objective for this chapter was also successfully achieved.

Due to a correlation co-efficient of 0.9021 between the two bioclimatic variables, precipitation and humidity, humidity was expected to be the bioclimatic variable with a stronger percentage predictive contribution compared to temperature and vegetation (Umoh et al. 2013). Humidity variables such as Annual Mean Specific Humidity, Specific Humidity of Most Humid Month, Specific Humidity Mean of Most Humid Quarter and Specific Humidity Mean of Coldest Quarter were particular strong predictors of distributions of the African Pygmy Goose, Black Stork, Lesser Jacana, Saddle Billed Stork and Pink Backed Pelican. Suitable wetland habitat which includes water availability is a requirement for waterbirdecology (Morton et al.1993). Wetland habitats characterized by high precipitation and humidity occurrence events, are positively correlated with waterbird distribution (Tian et al. 2019). Areas linked to high amounts of precipitation are important for waterbirds' feeding and breeding (Gerson and Guglielmo 2011; Wen et al. 2016). Precipitation and humidity are important environmental variables that determine habitat characteristics such as vegetation composition and cover, which is used by waterbirds for feeding and breeding (Rajpar and Zakaria 2014). The highpercentage predictive contributions of the humidity variables mean that these variables are most likely to have a strong influence on waterbird distribution ecology (Tian et al. 2019). Discussed below are the specific humidity variables and their influence on the particular waterbird distribution ecology, with waterbird ecological habits that support this statement.

For the African Pygmy Goose distribution, annual mean specific humidity and specific humidity mean of most humid quarter were strong environmental predictors of this waterbird's distribution.In general, this waterbird has dispersive movements dictated by habitat and water availability during the dry season as well (Carboneras and Kirwan 2014). Parts of the North-Eastern KwaZulu-Natal have experienced a decline in rainfall over a 15-year period that has had detrimental effects to habitat availability for the African Pygmy Goose (Taylor et al.2015). The African Pygmy Goose is not common in North-Eastern South Africa since permanent populations will only occur on the Nyl River floodplain and Kruger National Park, given sufficient rainfall (Taylor et al.2015). The regional population fluctuates greatly in response to rainfall and availability of pans in North Eastern KwaZulu -Natal (Carboneras and Kirwan 2014).

Specific Humidity of Most Humid Month and Specific Humidity Mean of Most Humid Quarter had a high percentage predictive contribution values towards the Black Stork distribution. Black Stork populations rely on areas containing permanent waterbodies for foraging (Lohmus and Sellis 2003). MaxEnt showed that Annual Mean Specific Humidity and Specific Humidity Mean of Most Humid Month variables to have had high percentage predictive contributions towards the Lesser Jacana distribution as well. According to a similar MaxEnt study on the Pheasant tailed Jacana by Tsai-Yu et al. (2012), the distribution of this Jacana species distribution is dependent on precipitation variables which encourage pond formation and vegetation. The Lesser Jacana prefers to inhabit areas with shallow waters around edges of permanent and seasonally flooded wetlands (Allan 1996).According to Allan (1996),local movements of the Lesser Jacana are dependent on rainfall events and species can be entirely absent during times of drought.

The Specific Humidity of Most Humid Month and Specific Humidity Mean of the Most Humid Quarter had the strongest percentage predictive contribution for the Saddle Billed Stork. Saddle Billed Storks display nomadic movements and move in response to feeding opportunities and drought conditions (Wen et al. 2016). A similar study done using MaxEnt noted that wetlands were more highly suitable for White Stork distribution compared to other habitat types (Zheng et al. 2016). Increasing drought conditions can adversely affect the range of available habitats for this species (Wen et al. 2016).

The MaxEnt results show humidity variables such as Specific Humidity Mean of Most Humid Quarter and Specific Humidity Mean of Coldest Quarter to have the highest percentage predictive contribution for the Pink Backed Pelican. Another MaxEnt study noted Pelican species distributions are controlled by the amount of inland wetlands present in Australia and that distribution becomes concentrated around coastal catchments due to the inland wetland no longer suited for Pelican ecological needs (Wen et al. 2016) The Pink Backed Pelican depends on precipitation that form floods around trees needed for breeding (Williams and Borello 1997b). Precipitation in December -

January period provides the appropriate conditions for their breeding life cycles (Williams and Borello 1997b).

Certain temperature variables such as temperature seasonality, temperature annual range, minimum temperature of the coldest month, mean temperature of the wettest quarter, mean temperature of the warmest quarter had high percentage predictive contribution values towards certain waterbird distributions such as the African Marsh Harrier, Great White Pelican and Wattled Crane. Discussed below are the specific temperature variables and their influence on the particular waterbird distribution ecology, with waterbird ecological habits that support this statement.

The temperature variables had a strong percentage predictive contribution towards certain waterbird distributions. Temperature seasonality and Temperature Annual Range percentage predictive contributions were high for the African Marsh Harrier. African Marsh Harriers are rarely found in dry areas, with habitats such as wetlands playing an important role in their breeding (Simmons 2005). Increases in temperature from climate change is suspected to negatively affect this species as reduced runoff into their wetland habitats will cause a reduction in breeding activity in small mammals, which African Marsh Harriers prey on (Simmons 2005). A study using MaxEnt on Marsh Harrier species noted that these constraints had a similar effect on the African Marsh Harrier's distribution (Cardador et al. 2014). The difference in temperature across South Africais a result of the contrasting oceanographic patterns on the east and west coasts (Reason and Mulenga 1999). Waterbirds relocate to different locations when seasonality fluctuates (Cardador et al. 2014). Precipitation or humidity variables would be expected to have been more stronger predictors of the African Marsh Harriers distribution compared to temperature variables since the African Marsh Harrier is absent from areas with <300mm of annual rainfall, indicating its tendency to distribute as a result of change in precipitation events across seasons (Simmons 2005).

The Minimum Temperature for the coldest month had strong percentage predictive contribution values towards the distribution of the Great White Pelican. The Minimum Temperature of the coldest month affects waterbird distribution as waterbirds do not cope well in extreme cold environments (Malcolm et al. 2006). They cannot maintain a suitable body temperature needed for metabolic functioning (Olivero et al. 1998). Droughts and places of extreme cold temperatures have been linked to restricted food availability and breeding failure of the Great White Pelican (Taylor et al. 2015).

The model output of the Wattled Crane species was the most accurate model. This could be because of the many presence-only distribution points and the way this species distribution points are located in relation to the environmental variable data when using its computational statistics to generate the SDM of this species (Phillips et al. 2006). According to the results, the Mean Temperature of the wettest quarter and Mean Temperature of warmest quarter showed high percentage predictive contribution values towards the Wattled Crane distribution. Although temperature variables are important for the thermoregulation of Crane species, a humidity/precipitation variable would be equally important for the Wattled crane species distribution since it depends on high rainfall events to keep habitat flooded which produces abundant resources (Stabach et al.2009) The Wattled Crane breeding pairs in KZN requires areas where rainfall averages 925mm per year (Morrison and Bothma 1998). These high rainfall areas, coupled with poor surface drainage, has provided suitable wetland sedge habitat for this species (Meine and Archibald 1996). The high percentage predictive contribution of the warmest quarter is also supported by literature for the Wattled Crane. Wattled cranes require sufficient heat in their environment for their egg laying (Meine and Archibald 1996).

3.11 Conclusion

According to literature, it is evident that certain temperature and humidity and precipitation and vegetation variables are important to waterbird distribution and ecology (Taylor et al.2015; Wen et al. 2016; Rajpar and Zakaria 2014). Due to the strong percentage predictive contribution of vegetation and humidity variables for waterbird distribution, the NFEPA wetland vegetation GIS layer would have been useful to run in MaxEnt for these waterbird species (Nel et al. 2011). This dataset was discovered after the analysis had already been done. Humidity and temperature bioclimatic variables were both strong variable predictors to certain waterbirds' distributions. The results generated by MaxEnt for this study, stating that humidity variables were stronger predictors to waterbird distribution compared to temperature variables, was supported by literature (Zheng et al. 2016). All of the SDMs had an average test and training AUC value above 0.7, which is more than that of a random model (Peterson et al. 2005).Vegetation cover percentage contribution was not expected to exceed the percentage contribution of humidity and temperature for most of the waterbird distributions in this study. It would have been more effective to use a much finer dataset like vegetation biomes instead since the scale of data affects the predictive accuracy of the MaxEnt model (Kumar et al.2014). In general, humidity variables such as the coldest months, wettest quarter, most humid quarter and coldest quarter were strong predictor variables for most of the waterbird distributions. However, temperature variables such as temperature seasonality and temperature annual range were strong predictor variables for the African Marsh Harrier, Great White Pelican and Wattled Crane.Literature has agreed with these results in that certain waterbirds do require certain ecological conditions to survive such as sufficient amounts of warm temperatures and humidity (Malcolm et al.2006; Wen et al. 2016). However, humidity variables are stronger drivers for African Marsh Harrier distributions since rainfall events control their habitat availability which ultimately drives their ecology (Simons 2005). High spatial and temporal variability in humidity and temperature has always made finding suitable habitat for waterbirds a challenge in environmental management (Pearson et al. 2006). Although some environmental variables had higher percentage predictive contributions towards certain species, none of the environmental variables had a percentage predictive contribution of 0. It is therefore clear that waterbirds rely on a combination of these environmental variables for their distribution ecology in their wetland habitat, with vegetation and humidity variables having higher predictive powers. The aforementioned would be considered more fundamental towards these waterbirds' distribution ecology (Malcolm et al.2006). Based on this study, ecological niche modelling using presence only data provides a useful amount of information on predicting the distributions for these threatened waterbird species (Zaniewski et al. 2002; Pearson et al.2006). Although humidity and precipitation environmental processes have a high correlation coefficient of 0.9021, it would have been more useful to use precipitation as the environmental variable since this variable is more directly related to waterbird distribution as mentioned in the literature above (Wen et al. 2016). Nonetheless, these predicted distributions generated by MaxEnt are useful in directing future conservation planning decisions which can assist environmental management in better planning for waterbirds (Phillips et al.2006; Cardador et al. 2014).

4 Assessing current protected areas and a Marxan best solution using a Marxananalysis

4.1.1 Aims

Aim 1: Toassess the adequacy of the IBAs, protected areas and PANs in protecting the observed and modelled conservation features.

Aim 2: To assess the adequacy of a Marxan best solution in protecting the observed and modelled conservation features.

Aim 3: To assess which reserve network design adequately protects all of the 10 threatened waterbird species best and aligns the best with the CARE principles of Systematic Conservation Planning.

4.1.2 Research Questions

Research Question 1: Using Arcmap 10.3, what is the condition of the South African landscape based on the 2013/14 DEA landcover used in this thesis?

Research Question 2: Does the existing IBA network adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 3: Does the existing protected area network adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 4: Does the existing PAN adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 5: Would a reserve network designed from conception using Marxan adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 6: Would an expanded PAN designed using Marxan adequately protect the 10 threatened waterbird species and does this reserve network align with the CARE principles of systematic conservation planning?

Research Question 7:

Is the reserve network of Marxan the best reserve network configuration for the 10 threatened waterbirds? Or should the planning units of the Marxan solution be used to complement the existing IBA and protected area networks?

4.1.3 Objectives

Objective 1: Using Arcmap 10.3 to assess the condition of the South African landscape based on the 2013/14 DEA landcover.

Objective 2: Using Marxan to assess whether the current the existing IBA network adequately protects the 10 threatened waterbird species and if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 3: Using Marxan to assess whether the current the existing protected area network adequately protects the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 4: Using Marxan to assess whether the existing PAN (Protected Area Network) adequately protects the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 5: Using Marxan to design a reserve network from conception that adequately protects the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 6: Using Marxan to expand on the existing PAN in order to adequately protect the 10 threatened waterbird species and assess if this reserve network aligns with the CARE principles of systematic conservation planning.

Objective 7: To assess which reserve network design adequately protects all of the 10 threatened waterbird species best and aligns the most with the CARE principles of Systematic Conservation Planning.

4.1.4 Hypothesis

A reserve network designed from conception by Marxan would be more spatial efficient and would more adequately protect all 10 waterbirds and contain all the reserve network good practice "CARE" principles than the IBA and current protected area networks. Additionally, a reserve network designed from conception by Marxan would complement the existing IBA and protected area networks.

4.1.5 Predictions

Prediction 1: The current PANs are spatially efficient and adequately protect the 10 threatened waterbirds.

Prediction 2: A Marxan reserve design approach would adequately protect all 10 threatened waterbirds more efficiently than the IBA and current protected area networks.

Prediction 3: A reserve system designed by Marxan is not solely the best reserve network for the protection of the 10 threatened waterbirds by itself but instead its planning units could complement the existing IBA and protected area networks.

4.2 Abstract

Marxan is decision-support software used for reserve network design. Good practice in systematic conservation planning suggests that reserve network design should follow the Connected, Adequate, Representative and Efficient or "CARE"principles. Marxan was used to assess the current protected area networks, namely the IBAs and the protected areas and a combination of both these networks, which was termed "PANs". Thereafter Marxan was used to design a reserve network from conception using the "CARE"principles of systematic conservation planning and assess how it could complement the current IBA and protected area networks. A combination of modelled and observation-based conservation features were used.Targets of a 100%, 80% and 50% were set for Critically Endangered, Endangered and Vulnerable categories for the 10 observation-based freshwater wetland threatened waterbird species. A target of 30% was set for Critically Endangered, Endangered and Vulnerable categories for the 10 modelled-based freshwater wetland threatened waterbird species.Since the White Winged Fluttail was not run in MaxEnt, it was also not analysed in Marxan. The number of conservation features used in the Marxan analysis was therefore 10 and not 11. Non-natural landcover categories, Eskom and Renewable GIS spatial data was used to develop the cost layer for Marxan and pentads were used as the planning units. The majority of South African landscape consisted of natural landcover according to the GIS analysis. After running Marxan, the maps showed that all reserve network scenarios showed high connectivity between planning units. The IBAs, protected area networks and PAN are not adequately meeting the threatened waterbird conservation targets. This is not what was predicted since South Africa is currently a leader in

systematic conservation planning, consisting of a community dominated by practitioners and influenced by academics. A reason why the existing reserve networks failed to adequately meet conservation targets could be because of the high targets set for the observation and modelled based conservation features. The Marxan best solution 2 generated from conception using Marxan, adequately protected and represented all 10 conservation features. Several important IBAs that are important for the conservation features breeding and feeding intersect with the Marxan best solution 2. South Africa has an active biodiversity stewardship programme which involves various private and communal landowners to protect biodiversity areas (SANBI 2015). With these stewardship programmes in place, a viable solution for the representation, functioning and persistence of waterbird ecology would be to use Marxan best solution 2, in order to complement the existing spatial footprint of existing network of IBAs and protected areas.

4.3 Introduction

The increased change of habitats and resource utilization induced by humans has increased the need to design adequate networks of conservation that prevent the further decline of biodiversity (Sakar et al. 2006). It is impossible to conserve all places that add value to biodiversity, since conservation usually competes with other human land use interests in space (Margules and Pressey 2000). Before the development of current systematic conservation approaches, the addition of new land for reserves was based on subjective judgements of biodiversity value, or on criteria which is irrelevant to biodiversity value (Sarkar 1999). These criteria entailed scenic value, remoteness or low primary production potential (Sarkar 1999). These past approaches also failed to include all the conservation features necessary for particular reserve-design scenarios (Ferrier et al. 2000). It also precluded sufficient resources into areas of high conservation value (Margules and Pressey 2000). As a result, over the past two decades, systematic conservation planning dealt with these previous issues through having a detailed and robust framework (Botts et al. 2019).

Systematic conservation planning aims to conserve biodiversity features by identifying the best possible set of areas (planning units), with assigned targets to each biodiversity feature (Knight and Cowling 2007). However, anthropogenic land-use change is an ongoing process and as a result will continue to compete with biodiversity conservation (Margules and Pressey 2000). Due to this competition, several methods have been developed to explicitly identify sets of efficient and cost-effective priority areas for conservation (Margules and Pressey 2000). Current conservation tools now use complementarity-based algorithms as opposed to traditional conservation tools which used scoring approaches (Ferrier et al. 2000).

Complementarity is important for reserve network as it connects planning units (group of areas) to existing reserve systems. Based on a planning unit's biodiversity value, it could potentially add to representing biodiversity in the existing reserve network (Williams et al. 1996). Algorithms that are driven by complementarity are able to design efficient reserve networks which are composed of complementary planning units that allow a more efficient representation of biodiversity (Pressey and Nichols 1989). After assigning explicit objectives, these algorithms are able to look for under-represented conservation features to add to the existing reserve network, in order to represent all biodiversity features, while simultaneously adding the least amount of additional area to achieve this goal (Pressey and Nichols 1989). Algorithms have added a lot of value to the assessment of reserves in systematic conservation planning (Cabeza and Moilanen 2006). This is achieved by measuring the irreplaceability of planning units in a reserve which is an assessment of a set of a planning unit's ability in meeting a set of biodiversity targets if it is added to the reserve network (Cabeza and Moilanen 2006).

Marxan is a decision-support software used for reserve network design (Ball et al. 2009). Marxan is the most widely used conservation planning software in the world and is designed for solving complex conservation planning problems (Watts et al.2009). It can be used in various stages of the systematic conservation planning process (Watts et al. 2009). Its primary goal is to include a minimum set of planning units that meet targets for all biodiversity features in the reserve network design at the lowest cost (Ball et al. 2009). It uses a heuristic(simulated annealing) to solve the algorithm (Game and Grantham 2008).The algorithm surveys the entire set of planning units across a defined study area to approximate a collection of planning units to meet targets, also defined as the global optimum (Ball et al.2009). The solution with the lowest Marxan score out of a user-defined number of runs is called the best solution (Ardron et al. 2010). A reserve system that succeeds in meeting all of its biodiversity targets at an acceptable cost and compactness is defined as an efficient reserve system (Possingham et al. 2002). The Marxan score is calculated using Marxan's objective function (Game and Grantham 2008) (see Figure 14). Marxan uses simulated annealing to solve the algorithm (Possingham et al. 2002). It does this by undergoing a user-defined number of iterations to change the reserve design one planning unit at a time in order to assess if each change brings it closer to the global minimum (Possingham et al. 2002). The global minimum is the lowest possible score in the decision space, where "score" is defined as the "answer" value to the optimisation algorithm (Possingham et al. 2002).

Due to the fact that Marxan works by simulated annealing, Marxan can fall into a local minimum, needing to make "bad moves" that initially increase the score to ultimately reduce the score further and move closer to the global minimum (Pressey et al. 2007). However, the fewer iterations remaining in a run, the more risky it becomes that the algorithm will not be able to find a lower solution than the local minimum, and the more likely it is that the local minimum is a close approximation of the global minimum (Game and Grantham 2008). So essentially, the algorithm used by Marxan starts off hot and cools down, as it attempts to iteratively improve the initial random reserve design (Game and Grantham 2008). This best solution is derived by comparing a series of reserve designs with each other by using a formula known as the objective function (Game and Grantham 2008; Ardron et al. 2010) (See Figure 14). Iterative improvement and the heuristic algorithm are two types of algorithms often used when running Marxan (Ardron et al. 2010). A Heuristic algorithm is a sub-optimal algorithm used as a time saving strategy whereby Marxan keeps on adding planning units until biodiversity targets are met (Ardron et al. 2010). Iterative improvement is the other frequently used algorithm where a random change is considered by the algorithm to see if it will improve the value of the objective function (Ardron et al. 2010). If random change does improve the reserve system, then that change is accepted (Game and Grantham 2008). Redundant planning units are also removed from the reserve systems (Game and Grantham 2008).

$$\sum_{Sites} \text{Cost} + BLM \sum_{Sites} \text{Boundary} + \sum_{ConValue} CFPF \times \text{Penalty} + \text{Cost Threshold Penalty}(t)$$

Figure 14: Marxans Objective Function

In Figure 14, cost is the sum of costs assigned to each of the planning units included in the reserve system (Game and Grantham 2008). Boundary is the total length of boundary surrounding the reserve system (Game and Grantham 2008). CFPF stands for Conservation Feature Penalty Factor. This is a weighting factor for the conservation feature which determines how important it would be to include it in the reserve plan (Ardron et al. 2010). Penalty refers to the cost and boundary length to adequately reserve a conservation feature which has not already been included in the reserve plan (Ardron et al. 2010).

4.4 Input data

The input data required to run a Marxan analysis include:

- Planning units are grid cells of the defined study area. Each grid cell has the potential of becoming a component of the final reserve plan (Ardron et al 2010).
- Conservation features are measurable elements of biodiversity that are selected as a focus for conservation planning (Game and Grantham 2008). This can be any process or element that can be measured in a planning unit such as species, habitat types, ecological classifications or physical features (Ardron et al 2010).
- Conservation targets are the values set for each conservation feature to be achieved in the final reserve solution (Ball et al. 2009)
- Cost is defined as the cost of including a planning unit in a reserve system. Cost could reflect any socio-political constraints, setting aside that specific planning unit for conservation action (Ardron et al 2010). Each planning unit is assigned a cost value; however, a planning unit may contain a combined cost value. Total area or any social, economic or ecological measure can represent cost (Ardron et al 2010).
- Boundary Length Modifier (BLM) is a penalty weighting in the algorithm that penalizes Marxan for having a long boundary length in its solution (Ball et al. 2009). This BLM variable controls the amount of overall reserve system boundary length relative to the reserve system cost (Ardron et al 2010). The BLM calibration allows the user to find an optimum amount of clustering without increasing the cost of the reserve network excessively (Ball et al. 2009). The shorter the boundary length in the reserve allows more compactness and clumpiness of the design (Ball et al. 2009).
- Protected areas are areas of land such as special nature reserves, national parks, nature reserves and protected environments which are protected by law and are managed mainly for biodiversity conservation (Republic of South Africa 2004). These areas are considered formally protected according to the National Environmental Management Act (Act 57 of 2003)(Republic of South Africa 2004).
- IBAs are a group of areas identified through the Birdlife International IBA programme for the conservation of bird species (Taylor et al 2005). When the criteria were developed, the following requirements were necessary for every IBA (BirdLife International 2004). Each IBA had to contain a population of bird species that were globally threatened, have restricted ranges of <50000km^2,contain a community of birds from a particular biome and contain congregrations of birds, eg. Migratory waterbirds or breeding seabirds (Fishpool and Evans 2001; Taylor et al. 2005). Several planning, priority setting, conservation and monitoring efforts have been put into the programme by BirdLife, Government Institutions and NGOs

(Fishpool and Evans 2001). These sites are meant to ensure long-term viability for most of the world's bird species (Taylor et al 2005).

- Lastly, the projected co-ordinate system used for Marxan was Albers_24_18_32 GCSWGS (See Table 4).

4.4.1 Planning units

Pentads were used as planning units. Pentads are 5' by 5' grid cells (Animal Demography Unit 2007). The pentad shapefile of South Africa was obtained from the ADU (Animal Demography Unit 2007). There were originally over 18000 pentads, with a WGS 84 projection. Since the study area covers Lesotho and Swaziland, this was clipped using a shapefile of the South African boundary using the SA statistics shapefile (obtained from Statistics South Africa). After clipping the shapefile, there were 16829 pentads. The data was projected into Albers Equal Area Projection. A unique identity code and area in km² was calculated for each pentad.

4.4.2 The Boundary file and Boundary length Modifier

The boundary filewas created using ArcMarxan and used as an input file in Marxan. This file has three fields which are the ID of the two planning units that are adjacent to each other (id1 and id2) and the length of the boundary between them (boundary) (Ball and Possingham 2000). The BLM (penalty value) is the penalty weighting to the length of the overall boundary of the selected planning units, which is specified in the input file (Game and Grantham 2008). The BLM value ultimately affects the Marxan objective function score (Ball and Possingham 2000). The BLM value assiststhe algorithm in selecting contiguous planning units (Ball and Possingham 2000). Higher BLM values result in selecting more planning units that are clumped together, increasing the clumpiness of planning units resulting in a more compact reserve (Game and Grantham 2008). Boundary files were used in this study because all of the Endangered waterbirds' habitats have been restricted in some way (Taylor et al. 2015).Clumping is the minimum amount of conservation *features* required within adjacent planning units before that "clump" is considered to effectively contribute towards reaching the representation target for the conservation feature (Ardron et al 2010). There is no guarantee that these clumped planning units are of low cost (Game and Grantham 2008). The BLM is useful in that it finds the optimum amount of clustering in a reserve without increasing the cost of the total reserve network excessively (Ardron et al. 2010). The ArcMarxan toolbox (Apropos Information System Inc. 2016) was used to create the Boundary files. The input parameters used weresingle and full values of 1 were used for the boundary treatment. Nine Boundary files were created. For each boundary file, the BLM value was calibrated and assessed to see which Boundary file gave the lowest cost through a trade-off between reserve clustering and cost (Ardron et al. 2010).

4.4.3 Conserved planning units

Protected areas and IBA's were used to designate planning units as conserved in the Marxan planning unit input file. These planning units were locked into the solution. This is specified in the status field of the pu input file (Game and Grantham 2008). This is done so that they are automatically selected and included in the final solution (Game and Grantham 2008).

4.4.3.1 IBA's

The IBA 2015 shapefile, which is the latest IBA spatial dataset, was downloaded from: https://www.birdlife.org.za/what-we-do/important-bird-and-biodiversity-areas/media-and-resources/#1553597171790-6f83422a-a731. (Birdlife South Africa 2016). There were a total of 175 IBAs in the shapefile. All of these IBA's add up to an area of 142034 km^2. This was combined with the pentad shapefile using the union tool. A pivot table was then created in MS excel to calculate the percentage of IBA area falling within each planning unit (pu). The percentage of IBA falling within each planning unit was calculated by using the formula: IFERROR (IBA area/PU area)*100. The IFERROR statement eliminated all #div/0 errors.

4.4.3.2 Protected Areas

The South African 2018 protected dataset was downloaded from: https://egis.environment.gov.za/data_egis/data_download/current. (Department of Environmental Affairs 2016). There were a total of 1516 protected areas in the shapefile adding up to 115838 km^2. This was overlaid with the pentad shapefile using the union tool. A pivot table was then created in excel to calculate the percentage of protected areas falling within each planning unit. The percentage of protected area falling within each pu was calculated by using the formula: IFERROR (protected area/PU area)*100. The IFERROR statement eliminated all #div/0 errors.

4.4.4 Observation-based biodiversity feature targets

The same observation-based conservation features used in the MaxEnt chapter were used in this chapter (Animal Demographic Unit 2007). One hundred percent, 80% and 50% targets were assigned to CR, EN and VU categories respectively. These targets were derived from the Technical guidelines for CBA Maps: Guidelines for developing a map ofCritical Biodiversity Areas & Ecological Support Areas using systematic biodiversity planning (Driver et al. 2017) (Table 8). Species occurrence in pentads was analysed from a presence-absence approach. All duplicate latitude and longitude values were deletedusing Microsoft excel. All irrelevant columns were removed, leaving only the latitude, longitude and species name columns. These csv files were converted into species distribution point shapefiles in ARCMAP.

Observation-based conservation features were used to inform the modelled species distribution. The observation-based conservation features were run in Marxan along with the modelled-based conservation features as it ensured that Marxan selected sites within the modelled distribution where the waterbird species have been confirmed by the observation-based conservation features (Wilson et al. 2005).

Table 8: A list of the 10 conservation features. The number of pentads represents the number of observations made in a pentad per waterbird species and were based on the presence- only data. A pentad may only contain a maximum of one record per waterbird species. The target area is the percentage of the area of pentads which was determined using the threatened status VU, EN or CR. The target was 100% for CR, 80% for EN and 50% for VU.

Common name	BLSA Redlist status 2018	No. of pentads	Target no. of pentads	Area of pentads (km²)	Target area (km²)
African Marsh Harrier	EN	866	693	62882	50306
African Pygmy Goose	VU	85	43	6150	3075
Black Stork	VU	713	357	53330	26665
Great White Pelican	VU	242	121	16896	8448
Grey Crowned Crane	EN	743	594	55001	44001
Lesser Jacana	VU	44	22	3270	1635

Pink Backed Pelican	VU	98	49	7169	3585
Saddle Billed Stork	EN	277	222	21039	16831
Wattled Crane	CR	109	109	8171	8171
Yellow Billed Stork	EN	576	461	43525	34820

4.4.5 Modelled biodiversity features

The modelled-based conservation features generated using MaxEnt provides additional data for future conservation planning for these threatened waterbirds in the IBA and protected area network, respectively. Predictive models, such as those created using MaxEnt, are widely used in the field of applied ecology and conservation in predicting spatial patterns of species diversity in the face of environmental changes (Phillips and Dudik 2008).As seen in the MaxEnt results section, although model accuracy from the ROC curves are high, all modelled data should be used with caution (Peterson et al. 2005) as there are numerous assumptions that need to be met in order for a species distribution model to be considered accurate (Yackulic et al. 2012). Random sampling done across the landscape is the main assumption to be met in the presence-only species distribution modelling (Yackulic et al. 2012).

The average ASCII output files for all 11 sample files from MaxEnt's output results were imported into ArcMap. All 11 ASCII files were converted into raster float format. Using the raster calculator, the raster float file containing probabilities between 0 and 1 was converted to an integer grid with values between zero and 100 by using the following formula: Int(100*Raster float file). These probabilities were converted into percentages similarly to Renner and Warton 2013.

The integer raster float files were converted into polygon files. The projection was defined as a geographic WGS 84 for all polygon files. The pentad study area polygons and polygon species files were projected into Albers Equal Area projection. To qualify as conservation features, the polygon species files had to possess values >50 probability of occurrence. A new shapefile was created by selecting and extracting all polygon features that had a greater value than this minimum value of 50. These newly defined presence locations represented those species features which had a >50% probability of occurrence record.

All new species conservation features were spatially joined to the pentads planning unit shapefile. Within each pentad, where a species had more than one record, the count for that species was replaced with a value of one, since the analysis only accounted for presence or absence. Using ArcMap, the species input file for Marxan was created (Apropos Information System Inc. 2016), i.e. the spec.dat file. The White Winged Flufftail was excluded from the Marxan analysis due to insufficient distribution sample record data that is required to run MaxEnt.

The same protocol for setting targets for Marxan's observation-based targets were used for the modelled species data (Table 9). The targets were set for a proportion of species distributions. The following targets were used and specified in spec.dat file. 100% for CR, 80% for EN and 50% for VU.

Species input for Marxan was generated using Arc toolbox extension (Apropos Information System Inc. 2016). These species distribution point shapefiles were opened in ArcMap. It was compared to the pentads planning unit shapefile. All points not falling within a pentad were removed using the clip tool and the pentad shapefile as the input. Each species distribution point shapefile was joined to the pentad shapefile. Where individual species records exceeded a count of one in the pentads, they were replaced with a value of one using the find and replace tool in the attribute table of ArcMap. The reason for this was because the analysis only took into account if a species was present in a planning unit, regardless of how many times that particular species was recorded inside a pentad. The collectively joined species distribution and pentad shapefile was converted into the required input file using ArcMarxan extension. This generated the necessary input files namely puvsp.dat, spec.dat and puvsp_sporder.dat required for Marxan.

Table 9: Summary of modelled conservation features with threatened status and area (km²). A target of 30% was used for CR, EN andVU species.

Common name	**BLSA Redlist status 2018**	**No. of population /pentads(> 50% threshold)**	**Target number of pentads(30 %)**	**Total area of pentads (km²)**	**Target area (km²)**
African Marsh Harrier	EN	2945	884	203618	61085
African Pygmy Goose	VU	511	153	33630	10089
Black Stork	VU	3750	1125	272724	81817
Great White Pelican	VU	604	181	36228	10868

Grey Crowned Crane	EN	1688	506	121007	36302
Lesser Jacana	VU	509	153	33833	10150
Pink Backed Pelican	VU	615	185	41066	12320
Saddle Billed Stork	EN	488	146	35195	10559
Wattled Crane	CR	215	65	15450	4635
Yellow Billed Stork	EN	2110	633	156009	46803

4.4.6 Conservation targets

The Marxan cost input file had three columns, which were identity, cost and status. The combined weighted cost of the cost data file was set up in the standard identity, cost, and status layout for Marxan. All decimal places were set to zero, where applicable. Marxan did not run when decimal places were not set to zero. The INT function in MS excel was therefore applied to all costs before running in Marxan. The INT removed all decimal places. All status values were assigned a value of zero, to indicate availability for selection. Target values in the spec.dat file were determined by threat status according to the BLSA 2018 threatened list. The technical guidelines for CBA maps were used as a guideline for setting conservation targets (Driver et al. 2017). One hundred percent target may be set for Critically Endangered species, high targets maybe set for Endangered species and moderate targets for Vulnerable species. A target of 100% was assigned to all observed species that were Critically Endangered. A target of 80% was assigned to Endangered observed species. A target of 50% was assigned to Vulnerable observed species. According to Driver et al. 2017, high conservation targets (above 50%) should be set for modelled conservation features only when there is high confidence in the modelled data-set. See Figure 13(a-t), showing that all models generated were above an AUC of 0.7, indicating high model confidence. However, for this study, all targets for modelled conservation features were set to 30% (Table 9). The >50% probability of occurrence threshold used should therefore have been increased.

4.4.7 Planning unit cost

As per objectives 5 and 6, Marxan was used to design a reserve network from conception in order to achieve all biodiversity targets at minimal cost. Each planning unit in Marxan is assigned a cost (Ardron et al. 2010). Planning units of lower cost are those which have been assigned a higher level of biological integrity (Ardron et al. 2010). Major threats to waterbird ecology were collisions with Eskom powerlines, renewable energy structures and all non-natural land cover categories (Taylor et al.2015). All of these have contributed to the habitat loss or reduction in habitat quality for these waterbirds, with the exception of croplands as some species like the Grey Crowned Crane feed in cultivation lands (Taylor et al.2015). The three Marxan input cost variables were therefore land cover, renewable energy and Eskom powerline data. For this reason, the Marxan cost layer for waterbirds was developed by integrating these multiple cost factors into a single cost variable (Ardron et al. 2010).

4.4.7.1 Landcover

The 2013/2014 30 by 30m Landcover thematic grid GEO reprojected WGS 84 was downloaded from https://egis.environment.gov.za/data_egis/data_download/current. (Department of Environmental Affairs 2016). This TIF file was resampled using the land cover 2000 (available on the DIVA website), (cell size 0.0083 resolution). The purpose of resampling was to make the spatial dataset a smaller size. ArcGIS tended to freeze when skipping this step. This was converted into a polygon using the raster to polygon tool in ArcMap. The polygons were not simplified. The polygon landcover was projected into the Albers equal area projection. An area column in km^2 was calculated for each landcover classes in the attribute table using ArcGIS. The landcover shapefile was then overlaid with the pentad shapefile using the union tool. The area of landcover per pentad was recalculated. The dbf file of the combined pentad planning unit file and landcover layer was opened in excel and a pivot table of this dataset was created. In the pivot table, the unique identity for each planning unit was placed on the rows and the grid codes were used as the columns. The area values (km^2) of each landcover class were used as the sum of values criteria in the pivot table.

Within the pivot table, the following formula was applied in terms of threat severity. Landcover sub weighted formula: (%non-natural landcover per planning unit). Urban and mining landcover values were multiplied by a value of two, since these pose a higher level of threat to waterbird ecology (Taylor et al. 2015). Cultivation landcover was not multiplied by any factor, since species like the Grey Crowned Crane uses mixed wetland, grassland and cropland habitats (Filmer and Haultshausen 1992). Therefore the cost value is equal to the area of the cultivation. The Grey Crowned Crane nests within wetlands and feeds in wetlands close to grasslands and croplands (Morrison and Bothma 1998). All decimal points were removed. This cost column was copied and pasted in a new sheet along with the original planning unit id number from the pentad planning unit layer. The VLOOKUP function was used to match these landcover values with the respective pu id’s they fell into. The id of the landcover data did not align with the planning unit id. VLOOKUP was used to match each landcover id and associated cost with its respective planning unit. The VLOOKUP formula: =IFERROR (VLOOKUP (planning unit number, Sum (landcover id and associated cost columns; 2; FALSE) ;””) was used to match these landcover values with the respective id’s they were associated with.

4.4.7.2 Eskom powerlines

Eskom data was obtained from Eskom data suppliers (Riandi Venter pers. Comm). The three shapefiles were high voltage (44-132V), main transmission system (226-765V) and medium voltage (1-33V). All lines that overlapped outside the pentads were removed using the clip tool. All fields in the powerline data with status fields such as null, decommissioned, dismantled, or invalid were removed, as they did not pose a threat. Powerlines of all three voltage types were merged together. The merged shapefile was overlaid with the planning unit layer using the intersect tool in ArcMap. The dbf file of the combined pentad and Eskom powerlines data was opened and a pivot table was created. Within the pivot table, the following weighted formula was applied in terms of threat severity.

Since voltage is an indication of height and number of lines, the following formula was used to rank the 3 types of powerline data (Riandi Venter pers. Comm).Eskom sub weighted formula:PU= (6*(sum mainline)) + (4*(sum High voltage lines)) + (2*(sum medium voltage lines)).The id of the Eskom data did not align with the planning unit id. VLOOKUP was used to match each Eskom id and associated cost with its respective planning unit. The VLOOKUP formula: =IFERROR (VLOOKUP (planning unit number, Sum (Eskom id and associated cost columns; 2;FALSE);"") was used to match these Eskom values with the respective ids were associated with.

4.4.7.3 Renewable energy

The renewable energy spatial data was downloaded fromhttps://egis.environment.gov.za/data_egis/data_download/current (Department of Environmental Affairs 2016). Seven renewable energy sources namely solar CSP and PV, solar CPV, solar PV, onshore wind and solar PV, onshore wind and wind were isolated as separate shapefiles. All projects where the status was classified as 'elapsed' were removed. Polygons from the wind shapefile were ignored, since it already existed in the onshore wind shapefile. Three polygons from the solar PV shapefile overlapped with the onshore wind and solar PV shapefile. These were deleted as the onshore wind and solar PV shapefile either contained the exact same polygon or covered the solar PV joint to the onshore wind polygon. All project statuses that were classified as approved or in process were kept for the analysis. These renewable energy shapefiles were all projected into the Albers equal area projection. The union tool was used to combine these seven renewable energy shapefiles with the planning unit layer. The dbf file of the combined pentad and renewable was opened and a pivot table was created. Within the pivot table, the following weighted formula was applied in terms of threat severity. The renewable energy types each posed different levels of threats to waterbirds. The renewable energy types were then classified using expert consultation (Samantha Ralston-Patton pers.comm).Renewable energy sub weighted formula: (6* wind area)+(4*solar CSP area)+(2*solar PV area)+(6* onshore wind and solar PV area's) + (4*solar CSP and PV area's). VLOOKUP was not necessary since each planning unit correlates with a renewable energy value in the dbf files.

4.4.7.4 Final cost value

The three factors used, namely Eskom powerlines, non-natural landcover categories and renewable energy are not equally weighted in terms of their impacts on suitability for conservation. Marxan is indecisive if all the planning units in a study have more or less equal cost values (Ball et al. 2009). A standardised score was used for each of the three threat layers (landuse, Eskom and renewable energy), the formula for the standardised score is: (score for that pu/highest score for all pu)*100. These standardised cost value formulas were then further weighted according to the following formula: (2* relative Eskom cost) + (2* relative renewable energy cost) + (1* relative landcover cost), as per the Marxan best practice guidelines (Ardron et al. 2010). Renewable energy and Eskom powerlines cost values were multiplied by two due to several injury and mortality waterbird events (Riandi Venter pers. Comm) (Samantha Ralston-Patton pers.comm). Landcover was not multiplied by two here since the mine and urban landcover categories were already multiplied by two for mining and urban land-use types in the pivot table. All costs were positive values across all planning units. See Figure 15 for a map of a relative cost index to biodiversity. Refer to Figure 16 for a frequency distribution of cost value across planning units.

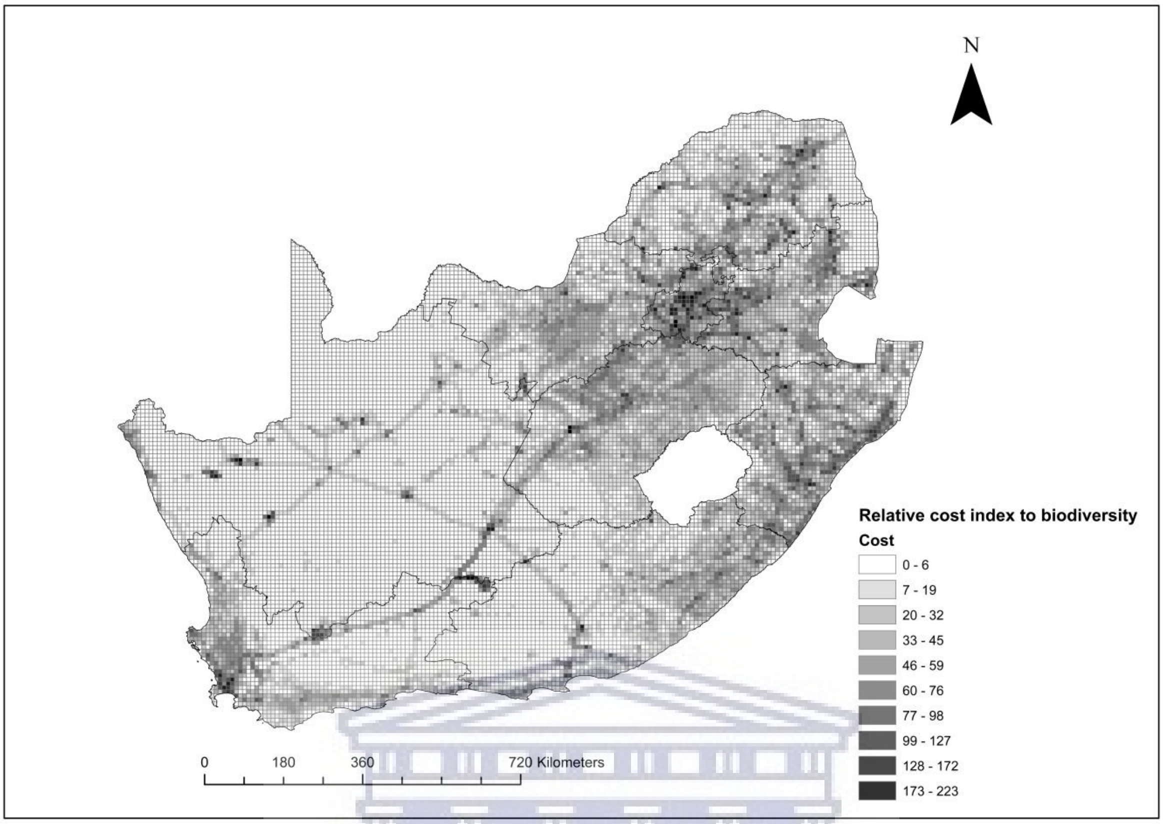

Figure 15: A relative cost index to biodiversity map consisting of three main threats to waterbird ecology, which were Eskom powerlines, non-natural landcover and renewable energy.

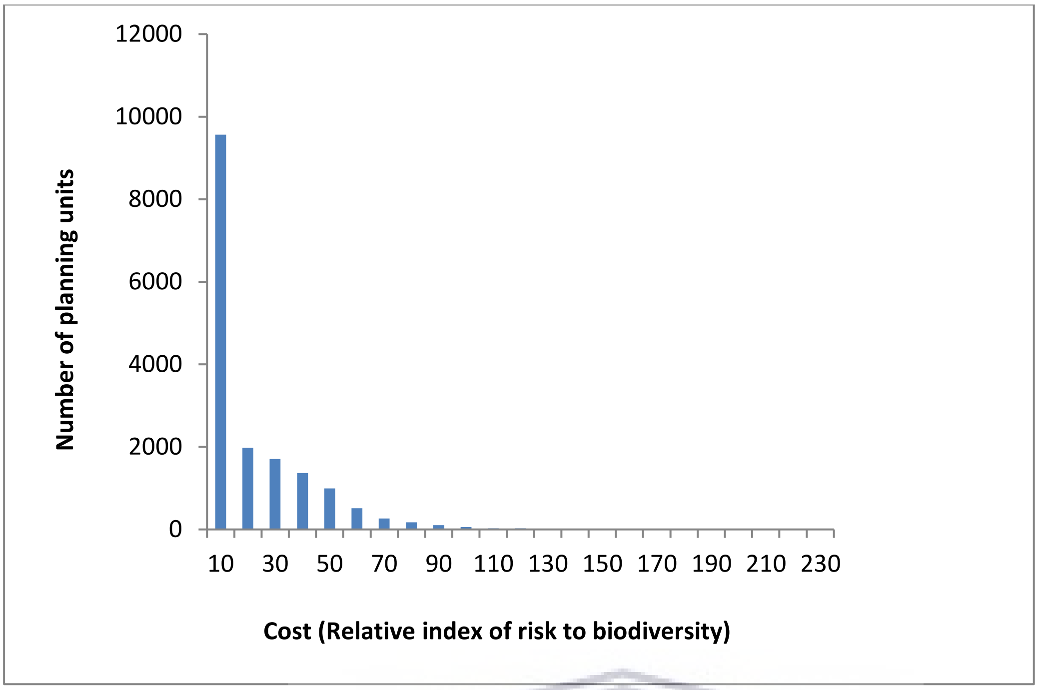

Figure 16: Frequency distribution of cost values across planning units. This dataset was non parametric and cost data is skewed to the right.

4.5 Calibrating Marxan

Conservation targets are assigned by the user in the spec.dat file. Boundary files are optional but if chosen to be used, it needs to be placed in the input file. In the boundary file, the BLM is the penalty weightingassigned to all the boundary measurements in the inedit.exe file (Game and Grantham 2008). For Marxan's best solutions, Marxan was calibrated to the "iterative improvement" setting in the inedit.exe for 100 repeat runs. For the protected area gap analyses, "greedy" heuristic algorithms were used to evaluate the protection status over one repeat run. Having too few iterations in these analyses could prevent Marxan from reaching the global optimum and essentially provide Marxan with enough "moves" to approximate the optimal solution (Game and Grantham 2008).In the analyses, Marxan was calibrated by using more iterations according to an order of magnitude. One million, 10 million, 100 million and 1 billion iterations were used to prevent the values in the "amount held" field being higher than the values in the "target" field of the Marxan output tables. However this did not help since the values in the "amount held" field still exceeded those in the "target" field of the Marxan output tables. Since increasing the iterations in an order of magnitude fashion made no difference, the number of iterations used for all 5 analyses was 1000000. IBAs and PAs were locked in by allocating a value of 2 in the status column of the pu.dat file. Zeros were assigned to the remaining pus in the pu.dat file. The same SPF calibration that was used in the Marxan best solution was applied in the PAN expansion as well. No BLM file was used in the PAN expansion (see BLM calibration). The simulated annealing and two-step iterative improvement was specified as the 'run type.'

4.5.1 BLM calibration

The 13 BLM files that were created were used in Marxan's input folder for the Marxan best solution scenario 2. Each BLM file was placed into a separate Marxan scenario. The values for the 13 BLM files were 0, 0.0001, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 10. See Figure 17 showing the trade-off between reserve system boundary length (km) and the average cost of the best solution reserve network. A BLM value of 0.8 was selected to be run in the Marxan scenarios.

The same 13 BLM files were created for the PAN expansion strategy scenario. However, the following error message appeared in Marxan's output_log.dat file, "Warning: Connection File boundary.dat not found 0 connections entered". A BLM was therefore not used for the PAN expansion strategy scenario when running Marxan.

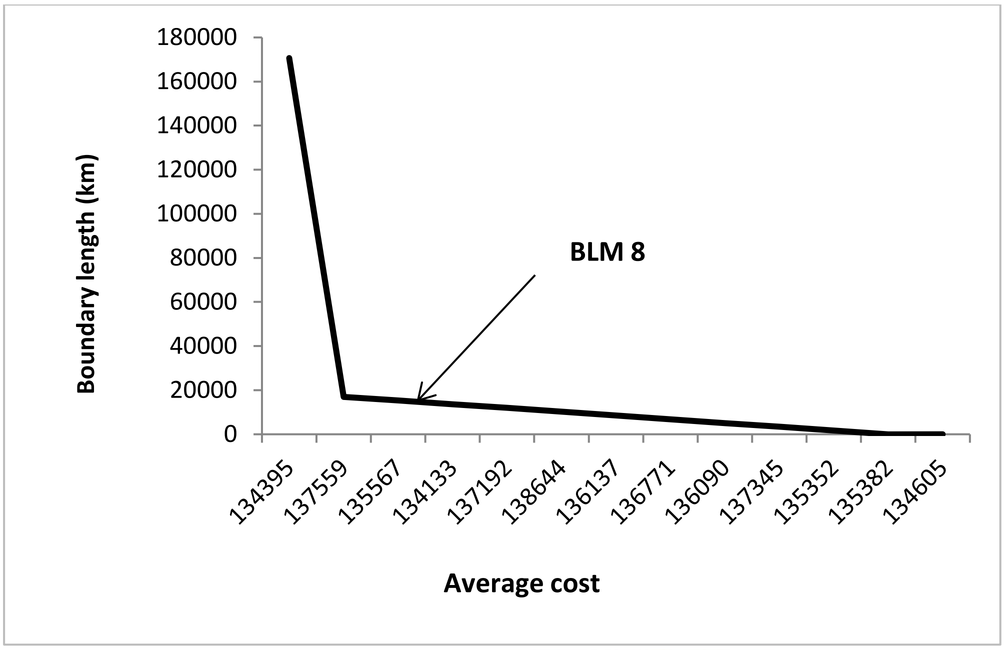

Figure 17: The trade-off between reserve system boundary length (km) and the average cost of the best solution reserve network. The average cost value is the average cost value per BLM scenario. As mentioned in the BLM calibration section of the Marxan best solution scenario 2, there were 13 BLM scenarios.

4.5.2 SPF calibration

When generating the Marxan best solution, the SPF value in the spec.dat was increased by a value of 1 for all conservation targets not met in the reserve plan. The SPF value was increased until all conservation targets for all conservation features were met. Marxan best solution scenario 1 was the first solution that Marxan generated before increasing the SPF. After increasing the SPF value, the Marxan best solution scenario 2 was created.

4.6 Data analysis

Five scenarios were considered for this data analysis. These five scenarios are: the protected area gap analysis, the IBA gap analysis, Protected Area Network (PAN) gap analysis, what the best reserve solution is to expand the existing PAN and what the most efficient reserve solution could have been if designed with Marxan from the outset. These five scenarios were used to assess how well the threatened waterbirds are conserved.

4.6.1 Protected areasgap analysis

Marxan can also be used to assess the current protection status of current protected area networks (Stewart et al. 2003; Game and Grantham 2008). In the Inedit.exe, a value of 1 was specified under the repeat runs tab since we assessed how well these areas were protected. A value of 0.95 was used as the "species missing proportion values if the target was lower than" value in the input file editor of Marxan. A heuristic algorithm was used and 'greedy' was specified as the heuristic algorithm. This fast method is appropriate for assessment purposes (Game and Grantham 2008).No BLM file was used, neither were parameters specified in the input.dat file. If >50% or more of a protected area fell within the pentad, the pentad would be considered to be a protected area. This was accomplished using a pivot table. In a new excel sheet, if the percentage protected area in a pu was greater than 50%, then it received a value of 2 (locked in final reserve plan) in the pu.dat Marxan status column. All pu's containing less than 50%, received a value of 3 (locked out final reserve plan) in the status column, concluding that the planning unit was not a protected area. No boundary length file was used.

4.6.2 IBAgapanalysis

In the input file parameter, a value of 1 in the repeat runs tab was specified for evaluating the IBAs reserves. A value of 0.95 was used as the "species missing proportion value if the target was lower than" value in the input file editor of Marxan. A heuristic algorithm was used, under the running options in the Inedit.exe, "Greedy" was specified as the heuristic algorithm. This fast method is appropriate for assessment purposes.If >50% or more of the IBA area of the pu fell within the pentad, the pentad would be considered to be an IBA. This was accomplished using a pivot table. In a new excel sheet, if the percentage of IBA in a pu was greater than 50%, then it received a value of 2 (locked in final reserve plan) in the pu.dat Marxan status column. All pu's containing less than 50% of IBA in a pu, received a value of 3 (locked out final reserve plan) in the status column concluding the planning unit was not an IBA. No boundary length file was used.

4.6.3 Protected Area Network (PAN) gap analysis

The purpose of this section of the Marxan analysis was to assess the protection status of the combined Protected Area Network. The combined PAN consists of IBA's and protected areas. For the PAN gap analysis solutions, the status field in pu.dat file contained 2's for the IBA's and protected areas. A value of three was assigned to planning units containing neither IBAs nor protected areas. A heuristic algorithm was used, under the running options in the Inedit.exe application. "Greedy" was specified as the heuristic algorithm. No boundary length file was used.

4.6.4 Using Marxan to expand on the existing PAN

The purpose of this analysis is to expand upon the existing PAN by looking for additional planning units to protect threatened waterbirds that were not protected in the PAN. To truly optimize the objective function efficiently, the Marxan algorithm needed to be calibrated (Ardron et al. 2010). For both optimal solutions, the status field in pu.dat file contained only zero's, giving Marxan freedom to choose across all planning units to achieve the lowest cost reserve design (Game and Grantham 2008). A value of 2 was assigned in the status field of the pu.dat file to all pu's which contained PANs. The simulated annealing followed by two-step iterative improvement algorithm was specified in the Inedit.exe. As already mentioned in the BLM calibration, no BLM was used. The Species Penalty Factor, which is a multiplier defined by the user that is applied to the objective function when a conservation feature is not met in the current reserve plan (Game and Grantham 2008). The SPF value was not increased since all conservation targets were met in the first scenario of the Marxan analysis.

4.6.5 Generating a Marxan best solution for the most efficient reserve solution

The purpose of this section of the Marxan analysis was to look for the most efficient configuration of sites to protect threatened waterbirds. To truly optimize the objective function efficiently, the Marxan algorithm needed to be calibrated (Ardron et al. 2010). For both optimal solutions, the status field in pu.dat file contained only zero's, giving Marxan freedom to choose across all planning units to achieve the lowest cost reserve design. The simulated annealing followed by two-step iterative improvement algorithm was specified in the Inedit.exe. The Species Penalty Factor is a multiplier defined by the user that is applied to the objective function when a conservation feature is not met in the current reserve plan. The SPF value was increased until all conservation targets for all conservation features were reached. A higher SPF value specified increases the chances of the reserve plan being more costly.

4.7 Results

4.7.1 SpatialNational Landscape Analysis

The Spatial analysis was done to calculate the area (km^2) of landcover categories across all pentads in South Africa. The total landscape area of South Africa is 1204604.37 km^2 (Table 10). The landscape of South Africa is mostly in a natural condition (Table 10). The South African landscape had a total non-natural landcover of 15.81%, with the highest amount of area contributed by cultivation (Table 10). A total of 84.18% of natural landcover was present in the landscape, with the majority of this landcover being composed of grasslands (Table 10). Waterbodies contributed 1.32% of the landcover in the landscape, with wetlands being the most dominant waterbody (Table 10). There are three Eskom powerline types across South Africa, each covering different lengths (Table 11). The total powerline length of the Eskom network was 383588 km^2. Medium Voltage powerlines were the most dominant powerline type, consisting of 78.53% of the Eskom powerline network **(**Table 11**)**. The two forms of predominant renewable energy across the South African landscape were solar and wind-powered types (Table 12). The total area of renewable energy structures in the landscape was 37219 km^2, with the majority renewable energy type being solar PV, 50.89 %, followed by onshore wind, 39.98 % (Table 12). Table 13shows that the total vegetation cover across the landscape was 1219478.38 km^2, with savannah and grassland being the dominant vegetation types contributing 32.08% and 26.88% respectively.

Table 10: Distribution of DEA 2014 landcover class area's across South Africa. Area km^2 is the area of each specific landcover class across South Africa in km^2 and percentage contribution of a specific landcover to a particular landcover class.

Non-natural landcover classes	**Area (km^2)**	**Percentage (%)**
Cultivation	139452.26	11.42
Mines	3299.84	0.27
Plantation	18653.06	1.52
Urban	29106.7	2.38
Non-natural landcover total	190511.88	15.81
Natural landcover classes	**Area (km^2)**	**Percentage (%)**
Bare non-vegetated	124188.3	10.17
Erosion	2198.28	0.18
Grassland	257834.66	21.12
Indigenous forest	4236.77	0.34
Low shrubland	366721.69	30.04
Shrubland Fynbos	52883.28	4.33
Thick dense bush	82014.15	6.71
Woodland open bush	124015.33	10.16
Natural landcover total	1014092.48	84.18
Water permanent	5104.77	0.41
Water seasonal	656.7	0.05

Wetlands	10144.17	0.83
Waterbodies total	15905.64	1.32
Grand total	**1204604.37**	**100**

Table 11: Distribution of Eskom powerline line length across all pentads in South Africa, where HV is High Voltage lines, MTS is Main Transmission System and MV is Medium Voltage lines. Line length (km²) is the line length of the powerline types existing across the pentads and the percentage of total area (%) is the percentage contribution of that specific type of Eskom powerline length.

Eskom	**Line Length (km²)**	**Percentage of total line length (%)**
HV lines	50028.61	13.04
MTS	32340.99	8.43
MV	301218.71	78.53
Total line length	383588.32	100

Table 12: Distribution of DEA 2017 renewable energy class area's across South Africa, where PV is Photovoltaic, CPV is Concentrator Photovoltaic and CSP is Concentrating Solar Power. Area (km²) is the area of the Renewable energy types existing across the pentads and the percentage of total area (%) is the percentage contribution of that specific type of renewable energy area to the total area.

DEA Renewable energy types classes	**Area (km²)**	**Percentage of total area (%)**
Onshore Wind and Solar PV	980.36	2.63
Onshore Wind	14881.3	39.98
Solar CPV	131.23	0.35
Solar CSP and PV	120.47	0.32

Solar CSP	2166.93	5.82
Solar PV	18939.64	50.89
Total area	37219.93	100

Table 13:Distribution of vegetation in South Africa using South Africa's National Vegetation Map 2011 (Mucina & Rutherford, 2011) areas across South Africa.Area (km²) is the area of the vegetation types existing across the pentads and the percentage of total area (%) is the percentage contribution of that specific type of Vegetation area to the total area.

Mucina Rutherford Biome Vegetation types	Area (km²)	Percentage of total area (%)
Albany thicket	29127.26	2.39
Azonal veg	31995.08	2.62
Desert	7165.60	0.59
Forest	4886.55	0.40
Fynbos	83219.01	6.82
Grassland	327797.39	26.88
Indian ocean belt	11440.01	0.94
Nama Karoo	248273.50	20.36
Savannah	391258.47	32.08
Succulent Karoo	83663.62	6.86
Waterbodies	651.88	0.05
Total area	1219478.38	100.00

4.7.2 Marxan analysis

Table 14to Table 18 contains the heading, conservation feature, target, amount held, target met and, minimum proportion met, specific to each Marxan scenario. The 5 Marxan best solutions were the IBA gap analysis, the protected area gap analysis, the PAN gap analysis, the PAN expansion strategy and theMarxan best solution scenario 2. The "target met" depicts whether or not the conservation feature met targets, using targets of 100%, 80% and 50% for the respective threatened categories (Game and Grantham 2008). The target no. of planning units is the number of planning units set by the user for Marxan to include in the final reserve network (Game and Grantham 2008). The Amount held is the actual number of planning units which Marxan included in its final reserve network (Game and Grantham 2008). The target met is a “yes” or “no” statement. Yes, if the MPM is greater than 0.95, and no, if the MPM was less than 0.95 (Game and Grantham 2008). The MPM value stands for the Minimum Proportion Met and is the highest proportion of the target that was included in the final reserve plan(Game and Grantham 2008). For a conservation feature target to be met, the MPM value needs to be above 0.95 (Game and Grantham 2008).

Table 14: Marxan protected area gap analysis. The target no. of planning units is the number of planning units set by the user for Marxan to include in the final reserve network. The Amount held is the actual amount of planning units which Marxan included in its final reserve network. The target met is a “yes” or “no” statement, “yes” if the MPM is greater than 0.95, and “no” if the MPM was less than 0.95.The MPM value stands for theMinimum Proportion Met and is the percentage of the target not included in the final reserve plan.For a conservation feature target to be met, the MPM value needs to be above 0.95.

Conservation Feature	Target	Amount Held	Target Met	MPM
African Marsh Harrier modelled	884	455	no	0.514706
African pygmy Goose modelled	153	179	yes	1
Black Stork modelled	1125	1040	no	0.924444
Grey Crowned Crane modelled	181	158	no	0.872928
Great White Pelican modelled	506	158	no	0.312253
Lesser Jacana modelled	153	156	yes	1
Pink Backed Pelican modelled	185	219	yes	1
Saddle Billed Stork modelled	146	363	yes	1
Wattled crane modelled	65	56	no	0.861538
Yellow Billed Stork modelled	633	739	yes	1
African Marsh Harrier observed	693	186	no	0.268398
African Pygmy Goose observed	43	35	no	0.813953
Black Stork observed	357	288	no	0.806723
Great White Pelican observed	121	85	no	0.702479
Grey Crowned Crane observed	594	93	no	0.156566

Lesser Jacana observed	22	23	yes	1
Pink Backed Pelican observed	49	40	no	0.816327
Saddle Billed Stork observed	222	236	yes	1
Wattled crane observed	109	24	no	0.220183
Yellow Billed Stork observed	461	258	no	0.559653

The gap analysis of the current protected area network in South Africa (see Figure 18), revealed that the majority of threatened waterbird species are inadequately represented in the protected area network. In fact, only 7 of the 20 species (20 represents modelled and observation conservation features) meet their conservation targets (Table 14). These 7 conservation feature targets that were adequately met, include the Saddle Billed Stork, Lesser Jacana observation-based features and the Yellow Billed Stork, Saddle-Billed Stork, Pink Backed Pelican, Lesser Jacana, and African Pygmy Goose modelled-based features. For the remaining 14 waterbirds, the MPM value shows that 4 waterbirds had less than 50% of its conservation targets met within the IBA reserve network (Table 14). This was the modelled-based distribution of the Great White Pelican and observation-based distributions of the African Marsh Harrier, Grey Crowned Crane and Wattled Crane.

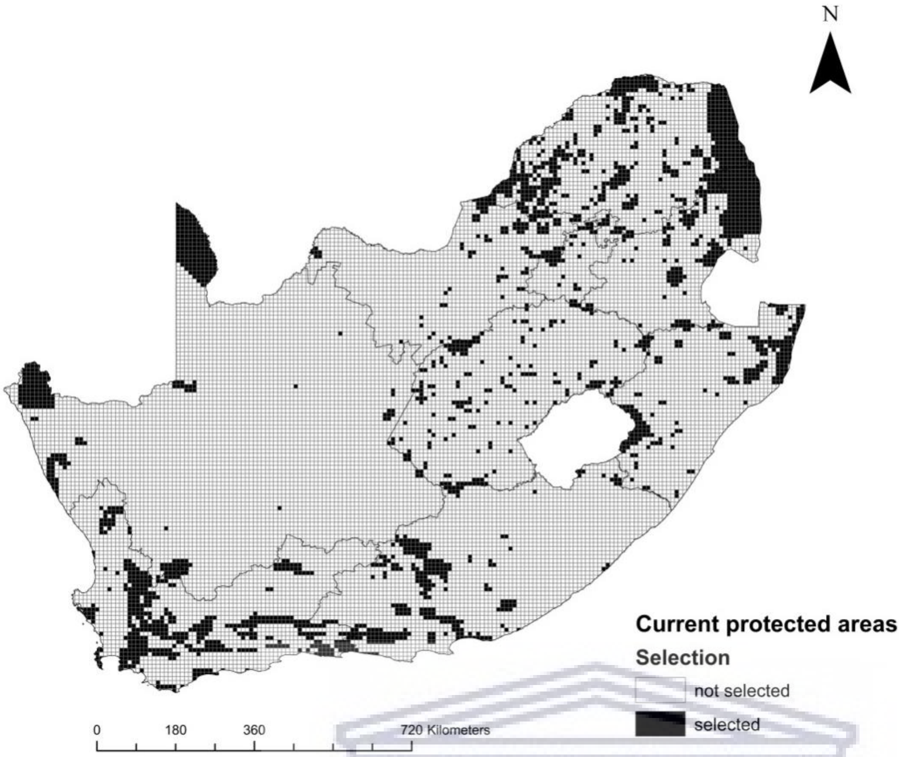

Figure 18: The current National protected areas network. https://egis.environment.gov.za/data_egis/data_download/current.(Department of Environmental Affairs 2016).

Table 15: Marxan IBA gap analysis. The target no. of planning units is the number of planning units set by the user for Marxan to include in the final reserve network. The Amount held is the actual number of planning units which Marxan included in its final reserve network. The target met is a "yes" or "no" statement, "yes" if the MPM is greater than 0.95, and "no" if the MPM was less than 0.95.The MPM value stands for theMinimum Proportion Met and is the percentage of the target not included in the final reserve plan.For a conservation feature target to be met, the MPM value needs to be above 0.95.

Conservation Feature	Target no. of (Planning units)	Amount Held (Planning units)	Target Met	MPM
African Marsh Harrier modelled	884	802	no	0.90724
African Pygmy Goose modelled	153	172	yes	1
Black Stork modelled	1125	1104	yes	0.981333
Grey Crowned Crane modelled	181	405	yes	1
Great White Pelican modelled	506	205	no	0.405138
Lesser Jacana modelled	153	158	yes	1
Pink Backed Pelican modelled	185	216	yes	1
Saddle Billed Stork modelled	146	346	yes	1
Wattled Crane modelled	65	88	yes	1
Yellow Billed Stork modelled	633	629	yes	0.993681
African Marsh Harrier observed	693	309	no	0.445887
African Pygmy Goose observed	43	41	yes	0.953488
Black Stork observed	357	338	no	0.946779
Great White Pelican observed	121	104	no	0.859504
Grey Crowned Crane observed	594	238	no	0.400673
Lesser Jacana observed	22	25	yes	1
Pink Backed Pelican observed	49	43	no	0.877551
Saddle Billed Stork observed	222	229	yes	1
Wattled Crane observed	109	48	no	0.440367
Yellow Billed Stork observed	461	245	no	0.531453

The gap analysis of the current IBA reserve network in South Africa (seeFigure 19), revealed that less than half of threatened waterbird species are inadequately represented in the IBA reserve network. The IBA reserve network adequately represents more species than the Protected area network. Twelve of the 20 species meet their conservation targets in the IBA network(Table 15). These 12 conservation feature targets that were met, include theSaddle Billed Stork, Lesser Jacana, African Pygmy Gooseobservation-based features and the African Pygmy Goose, Black Stork, Grey Crowned Crane, Lesser Jacana, Pink Backed Pelican, Saddle Billed Stork, Wattled Crane and Yellow Billed Stork modelled-based features. For the remaining 8 waterbird features, the MPM value shows that 4 waterbirds had less than 50% of its conservation targets met within the IBA reserve network (Table 15). These were modelled distributions of the Great White Pelican and observation-based distributions of the African Marsh Harrier, Grey Crowned Crane and Wattled Crane.

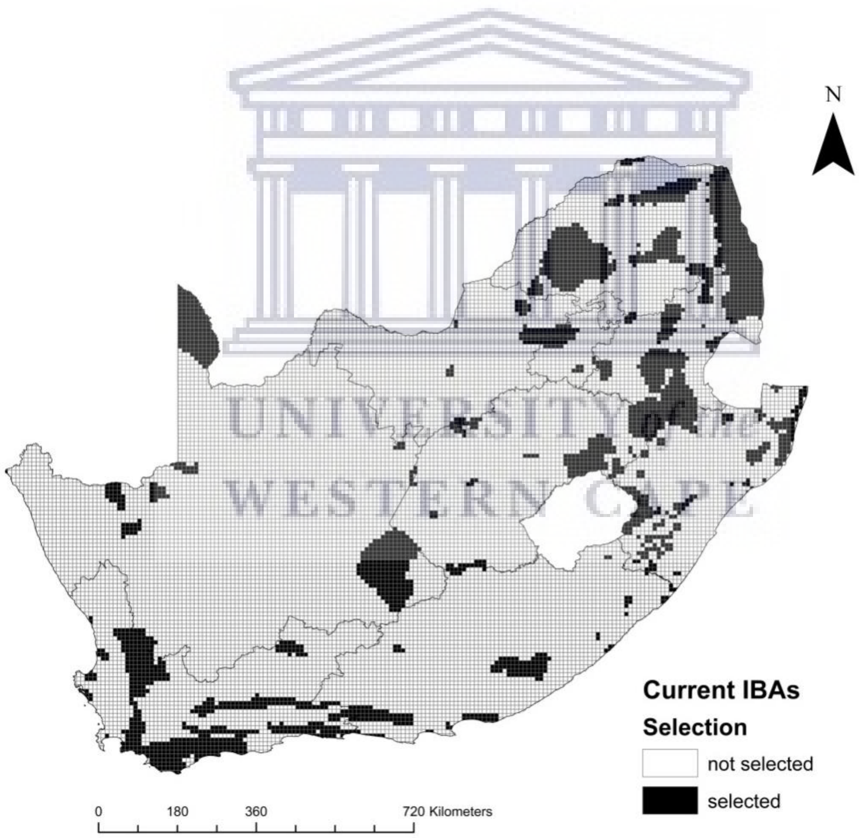

Figure 19: The current IBA network. https://www.birdlife.org.za/conservation/important-bird-areas/documents-and-downloads#. (Birdlife South Africa 2016).

Table 16: Marxan PAN gap analysis. The target no. of planning units is the number of planning units set by the user for Marxan to include in the final reserve network. The Amount held is the actual amount of

planning units which Marxan included in its final reserve network. The target met is a "yes" or "no" statement, "yes" if the MPM is greater than 0.95, and "no" if the MPM was less than 0.95.The MPM value stands for theMinimum Proportion Met and is the percentage of the target not included in the final reserve plan.For a conservation feature target to be met, the MPM value needs to be above 0.95.

Conservation Feature	Target	Amount Held	Target Met	MPM
African Marsh Harrier modelled	884	932	yes	1
African Pygmy Goose modelled	153	196	yes	1
Black Stork modelled	1125	1462	yes	1
Grey Crowned Crane modelled	181	440	yes	1
Great White Pelican modelled	506	240	no	0.474308
Lesser Jacana modelled	153	175	yes	1
Pink Backed Pelican modelled	185	240	yes	1
Saddle Billed Stork modelled	146	368	yes	1
Wattled Crane modelled	65	93	yes	1
Yellow Billed Stork modelled	633	878	yes	1
African Marsh Harrier observed	693	353	no	0.50938
African Pygmy Goose observed	43	44	yes	1
Black Stork observed	357	388	yes	1
Great White Pelican observed	121	124	yes	1
Grey Crowned Crane observed	594	259	no	0.436027
Lesser Jacana observed	22	27	yes	1
Pink Backed Pelican observed	49	48	yes	0.979592
Saddle Billed Stork observed	222	247	yes	1
Wattled Crane observed	109	52	no	0.477064
Yellow Billed Stork observed	461	305	no	0.661605

The gap analysis of the current PAN (Figure 20) in South Africa showed that 7 waterbird species are inadequately represented in these areas. Fourteen of the 20 species adequately met their conservation targets (Table 16). These 14 conservation feature targets that were adequately met include the African Pygmy Goose, Black Stork, Great White Pelican, Lesser Jacana, Pink Backed Pelican and Saddle Billed Stork observation-based features and the African Marsh Harrier, African Pygmy Goose, Black Stork, Grey Crowned Crane, Lesser Jacana, Pink Backed Pelican, Saddle Billed Stork, Wattled Crane and Yellow Billed Stork modelled-based features. The remaining 7 waterbirds conservation targets were not adequately met. Out of these remaining 7 waterbirds, the MPM value showed that 3 waterbirds had less than 50% of its conservation target met within the PAN network (Table 16). These were the modelled-based distributions of the Grey Crowned Crane and observation-based distributions of the Grey Crowned Crane and Wattled Crane. Refer toFigure 19for the map of PAN's.

Table 17: PAN expansion strategy. The target no. of planning units is the number of planning units set by the user for Marxan to include in the final reserve network. The Amount held is the actual amount of planning units which Marxan included in its final reserve network. The target met is a "yes" or "no" statement, "yes" if the MPM is greater than 0.95, and "no" if the MPM was less than 0.95.The MPM value stands for theMinimum Proportion Met and is the percentage of the target not included in the final reserve plan.For a conservation feature target to be met, the MPM value needs to be above 0.95.

Conservation Feature	Target	Amount Held	Target Met	MPM
African Marsh Harrier modelled	884	1475	yes	1
African Pygmy Goose modelled	153	317	yes	1
Black Stork modelled	1125	1811	yes	1
Grey Crowned Crane modelled	181	742	yes	1
Great White Pelican modelled	506	506	yes	1
Lesser Jacana modelled	153	294	yes	1
Pink Backed Pelican modelled	185	363	yes	1
Saddle Billed Stork modelled	146	398	yes	1
Wattled Crane modelled	65	157	yes	1
Yellow Billed Stork modelled	633	1050	yes	1
African Marsh Harrier observed	693	693	yes	1
African Pygmy Goose observed	43	67	yes	1
Black Stork observed	357	471	yes	1
Great White Pelican observed	121	194	yes	1
Grey Crowned Crane observed	594	594	yes	1
Lesser Jacana observed	22	40	yes	1
Pink Backed Pelican observed	49	79	yes	1
Saddle Billed Stork observed	222	260	yes	1
Wattled Crane observed	109	109	yes	1
Yellow Billed Stork observed	461	461	yes	1

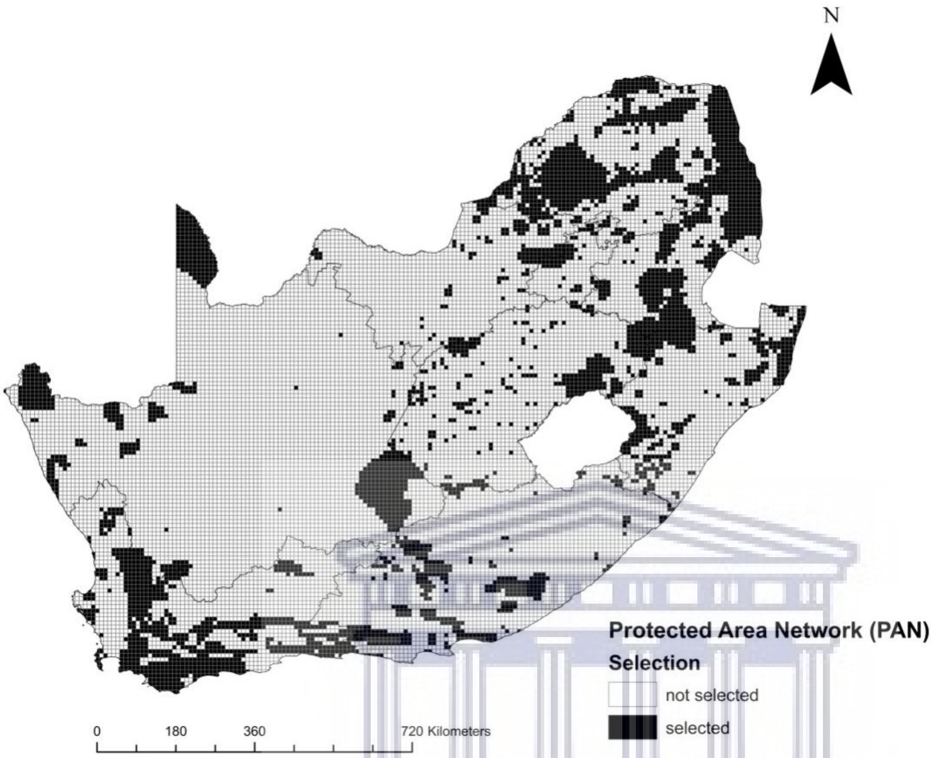

Figure 20: The current PAN, which consists of the IBA and National protected area network combined. https://www.birdlife.org.za/conservation/important-bird-areas/documents-and-downloads#. (Birdlife South Africa 2016). https://egis.environment.gov.za/data_egis/data_download/current.(Department of Environmental Affairs 2016).

Marxan was run to expand on the existing PANs in order to meet all targets not met in the PANs. The name of this network was termed the PAN expansion. The Marxan reserve network (Figure 21) result showed that it was a very "land hungry" solution, using nearly the entire KZN and Mpumalanga, most of Limpopo, close to half of Gauteng, Eastern Cape and Western Cape for conservation and more than half of the Northern Cape. Though this reserve network used up a vast majority of the land for conservation, it adequately met all of the 20 conservation feature targets(Table 17).

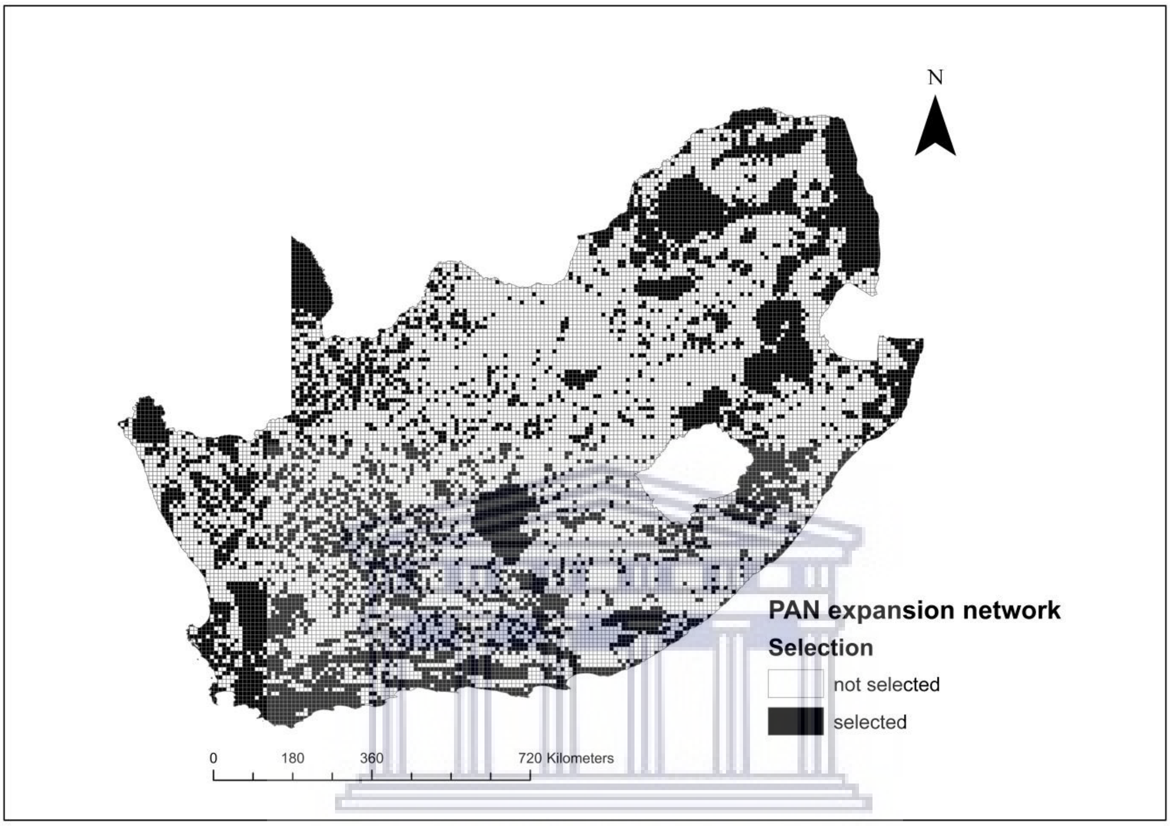

Figure 21: PAN expansion generated using Marxan. Planning units coloured in white are those that were not included in the PAN expansion network final reserve network, whereas those coloured in black are those that were included in the PAN expansion final reserve network.

In this section of the Marxan analysis, Marxan was run from conception, in order to design the most efficient configuration of sites to adequately protect the 20(observed and modelled) threatened waterbird conservation features. The BLM value was calibrated to 0.8, since it was the most balanced representation of clustering the reserve network with increasing cost. As seen inFigure 17, a BLM value of 0.8 is where there is a turning point at which reserve cost increases and becomes large, relative to the reduction in boundary length (Game and Grantham 2008). The SPF value was increased by one for all these conservation feature targets not met. As a result, all 20 conservation feature targets were adequately met for the Marxan best solution 2 (Table 18). SeeFigure 22,for a map of the Marxan best solution 2. Allconservation features had an MPM value of 1. For the Marxan best solution scenario 2, most planning units that were included in the final reserve plan, 81-100 % of the time were located in North West, Limpopo, Mpumalanga, Kwa Zulu Natal, Eastern Cape and Western Cape provinces (Figure 23).

Table 18: Marxanbest solution scenario 2. The target no. of planning units is the number of planning units set by the user for Marxan to include in the final reserve network. The Amount held is the actual amount of planning units which Marxan included in its final reserve network. The target met is a “yes” or “no” statement, “yes” if the MPM is greater than 0.95, and “no” if the MPM was less than 0.95.The MPM value stands for theMinimum Proportion Met and is the percentage of the target not included in the final reserve plan.For a conservation feature target to be met, the MPM value needs to be above 0.95.

Conservation Feature	Target	Amount Held	Target Met	MPM
African Marsh Harrier modelled	884	884	yes	1
African Pygmy Goose modelled	153	257	yes	1
Black Stork modelled	1125	1125	yes	1
Grey Crowned Crane modelled	181	474	yes	1
Great White Pelican modelled	506	376	yes	1
Lesser Jacana modelled	153	242	yes	1
Pink Backed Pelican modelled	185	298	yes	1
Saddle Billed Stork modelled	146	372	yes	1
Wattled Crane modelled	65	130	yes	1
Yellow Billed Stork modelled	633	633	yes	1
African Marsh Harrier observed	693	584	yes	1
African Pygmy Goose observed	43	49	yes	1
Black Stork observed	357	357	yes	1
Great White Pelican observed	121	126	yes	1
Grey Crowned Crane observed	594	492	yes	1
Lesser Jacana observed	22	31	yes	1

Pink Backed Pelican observed	49	62	yes	1
Saddle Billed Stork observed	222	226	yes	1
Wattled Crane observed	109	106	yes	1
Yellow Billed Stork observed	461	337	yes	1

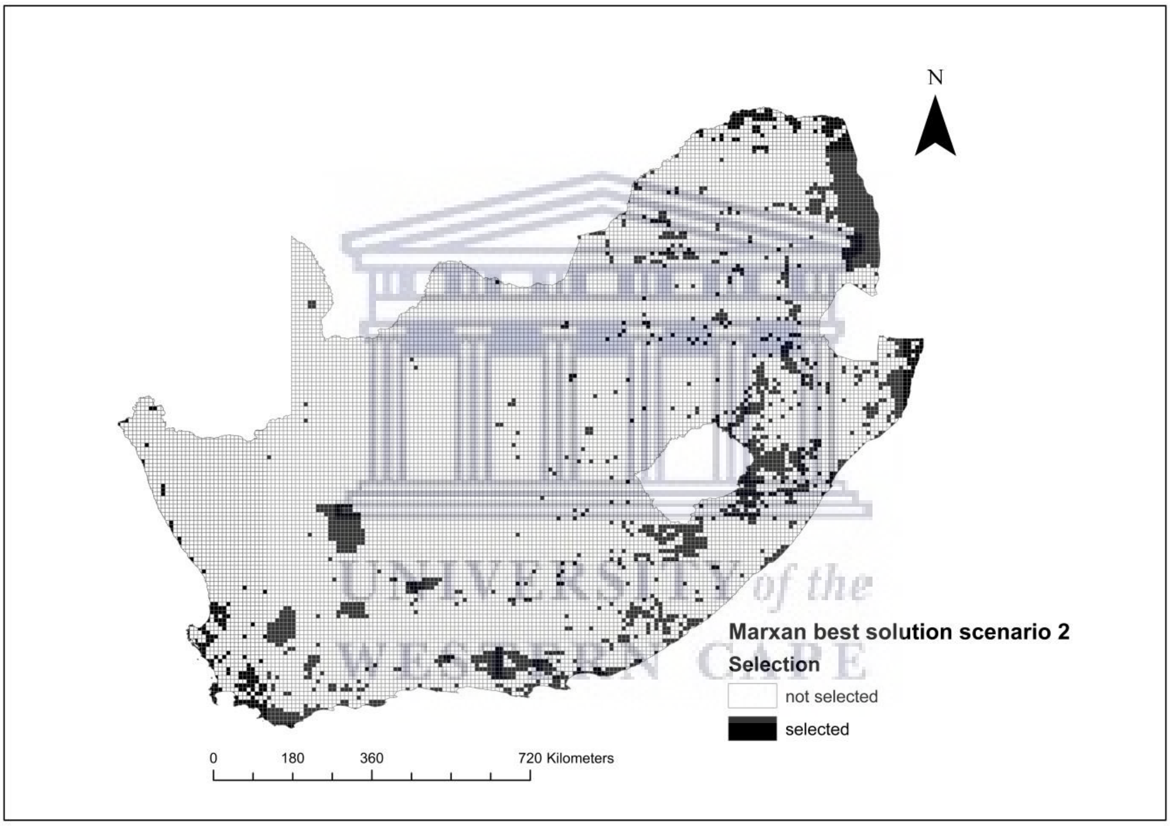

Figure 22: Marxan best solution scenario 2. Planning units coloured in white are those that were not included in the Marxan best solution 2 final reserve network, whereas those coloured in black are those that were included in the Marxan best solution 2 final reserve network.

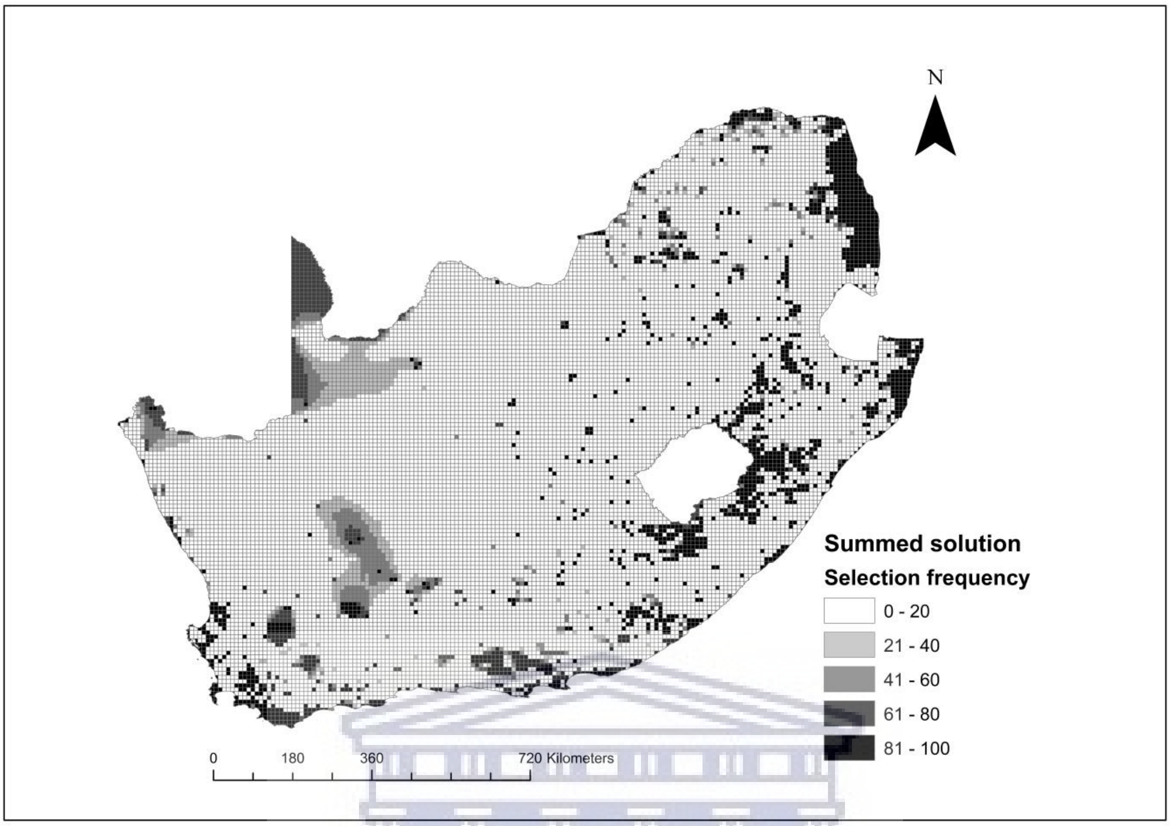

Figure 23: Summed solution selection frequency map for Marxan best solution scenario 2. Planning units with values with low selection frequency (closer to 0 and closer to the colour white) show that it was not frequently selected by Marxan in the final reserve network of the Marxan best solution over the 100 repeat runs.Planning units with values with high selection frequency (closer to 100 and closer to the colour black) show that it was frequently selected by Marxan in the final reserve network of the Marxan best solution over the 100 repeat runs.

Table 19: Marxan summary analysis for all reserves networks.The Area(km²) represents the area measured in km² for each reserve network. The cost is the relative index of risk to biodiversity consisting of Eskom powerlines, renewable energy structures and non-natural landcover categories (Figure 15). The number of observation-based conservation feature targets met is the number of observation-based conservation features Marxan included in that particular reserve plan. The number of modelled-based conservation feature targets met is the number of modelled-based conservation features Marxan included in that particular reserve plan. The number of planning units represents the actual number of conservation features expressed as planning units included by Marxan in each of the final reserve network.

Reserve network name	IBA Network	Protected area's	PAN	MarxanBest solution 2	PAN expansion
Area(km²)	185041	175528	278791	140877	470172
Cost	41581	24125	55049	19890	162791
Number of observation-based conservation feature targets met	4	6	6	10	10
Number of modelled-based conservation feature targets met	8	8	8	10	10
Number of planning units	2708	2425	3839	2082	6586

According to Table 19, the IBAs and protected area networks were relatively low in cost, small in area (km²) or weren't as "land hungry" solutions (land hungry solutions are those reserve networks contain a lot of planning units in its reserve network), compared to the PAN and PAN expansion strategy(Table 19). The combined IBA and protected areas network, also known as the PAN, were slightly lower in area, cost and number of planning units compared to the PAN expansion. The PAN managed to adequately protect 14 out of the 20(modelled and observed) conservation features in its network. The Marxan best solution 2 was the smallest and least costly network. It also included all 20 conservation feature targets in its reserve plan(Table 19). The Marxan best solution scenario 2 was the most efficient network compared to the other 4 networks as it conserved the same amount of conservation features at the lower cost and had a smaller total area (km²) (Table 19). Table19 shows that the difference in area (km²) between the PAN and PAN expansion was 191381 km².According to the PAN expansion, Marxan added a total area of 191381 km² of additional planning units to the PAN expansion. Thus the current PAN would need to be increased by more than 50% to meet the targets of all the conservation features in the PAN. If a BLM file was used for the PAN expansion, it would have reduced the total network cost and area.

The Marxan best solution scenario 2 consists of several planning units falling outside of the existing IBA network (Figure 24). A total of 33240 km² of IBA area exists in the Marxan best solution scenario 2. The type of IBA contributing the largest area to the intersection with the Marxan best solution scenario 2 was the Kruger National Park and adjacent areas (63.76%) (See Table 20). The Marxan best solution scenario 2 consisted of several planning units falling outside of the existing protected Area network as well (Figure 25). A total of 112436 km² of protected areas intersect with the Marxan best solution scenario 2. The protected area contributing the largest area to the intersection with the Marxan best solution 2 was National Parks (50.48. %) (See Table 21).

Table 20: Key IBA's important for waterbird ecology intersection with Marxan best solution 2. The area of intersection (km²), represents the area in (km²) for each key IBA. The percentage (%) is the percentage contribution of each IBA type to the entire IBA network.

Key IBA name	Area of intersection (km²)	Percentage (%)
Barberspan and Leeupan	231.00	0.69
Dassen Island	4.00	0.01
Hluhluwe-iMfolozi Park	979.00	2.95
iSimangaliso Wetland Park	4617.00	13.89
Kruger National Park and adjacent areas	21193.00	63.76
KwaZulu-Natal Mistbelt Forests	1415.00	4.26
KwaZulu-Natal Mistbelt Grasslands	1185.00	3.56
Magaliesberg	77.00	0.23
Mapungubwe	645.00	1.94
Nyl River Floodplain	234.00	0.70
Soutpansberg	632.00	1.90
Waterberg System	2028.00	6.10
Total area of entire IBA network	**33240.00**	**100.00**

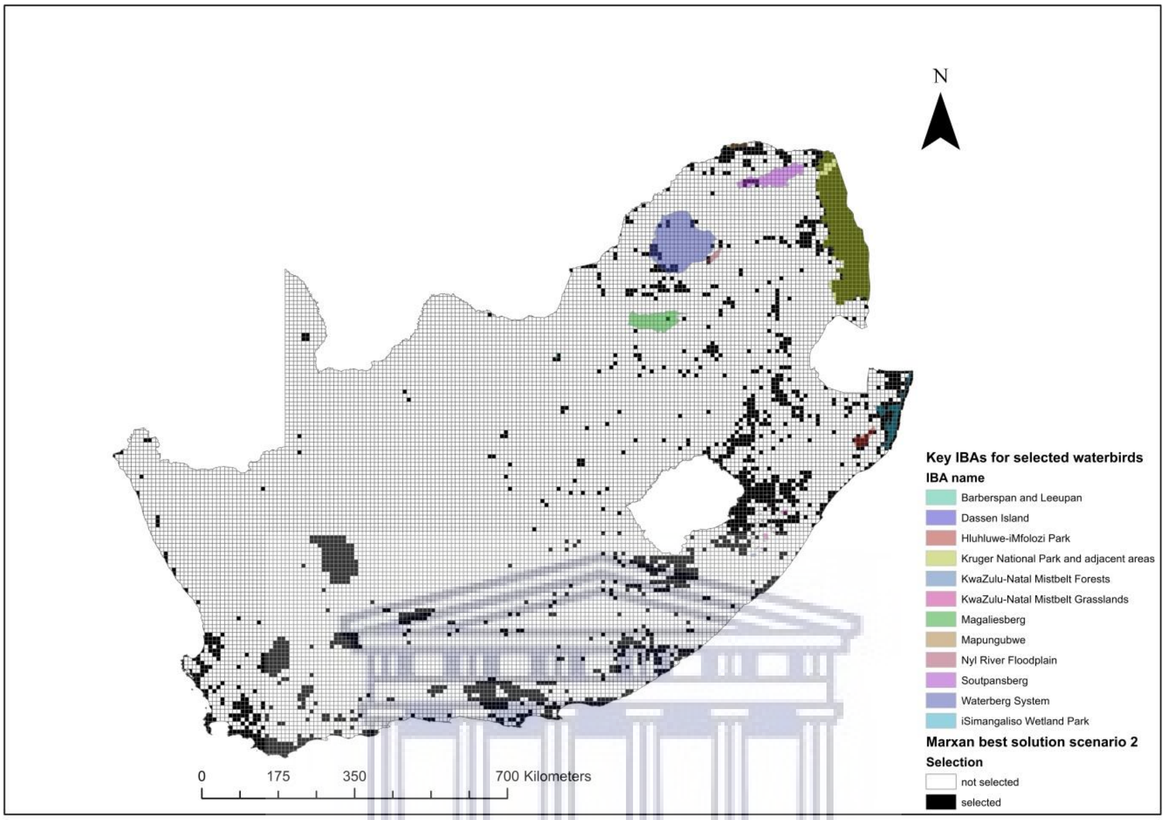

Figure 24: Key IBA's spatial association with the Marxan best solution 2. Planning units in green are those that were not included in the Marxan best solution 2 final reserve network, whereas those in red are those that were included in the Marxan best solution 2 final reserve network.

Table 21: Protected area intersection with the Marxan best solution 2. The area of intersection (km^2), represents the area in (km^2) for each protected area type. The percentage (%) is the percentage contribution of each protected area type to the entire protected area network.

Protected area site	Area of intersection (km2)	Percentage (%)
Forest nature reserve	6331.00	5.63
Forest Wilderness Area	4643.00	4.13
Mountain Catchment Area	8143.00	7.24
National Park	31352.00	27.88
Nature Reserve	56755.00	50.48
Protected Environment	5145.00	4.58
Special Nature Reserve	67.00	0.06
Total area of the entire protected area network	**112436.00**	**100.00**

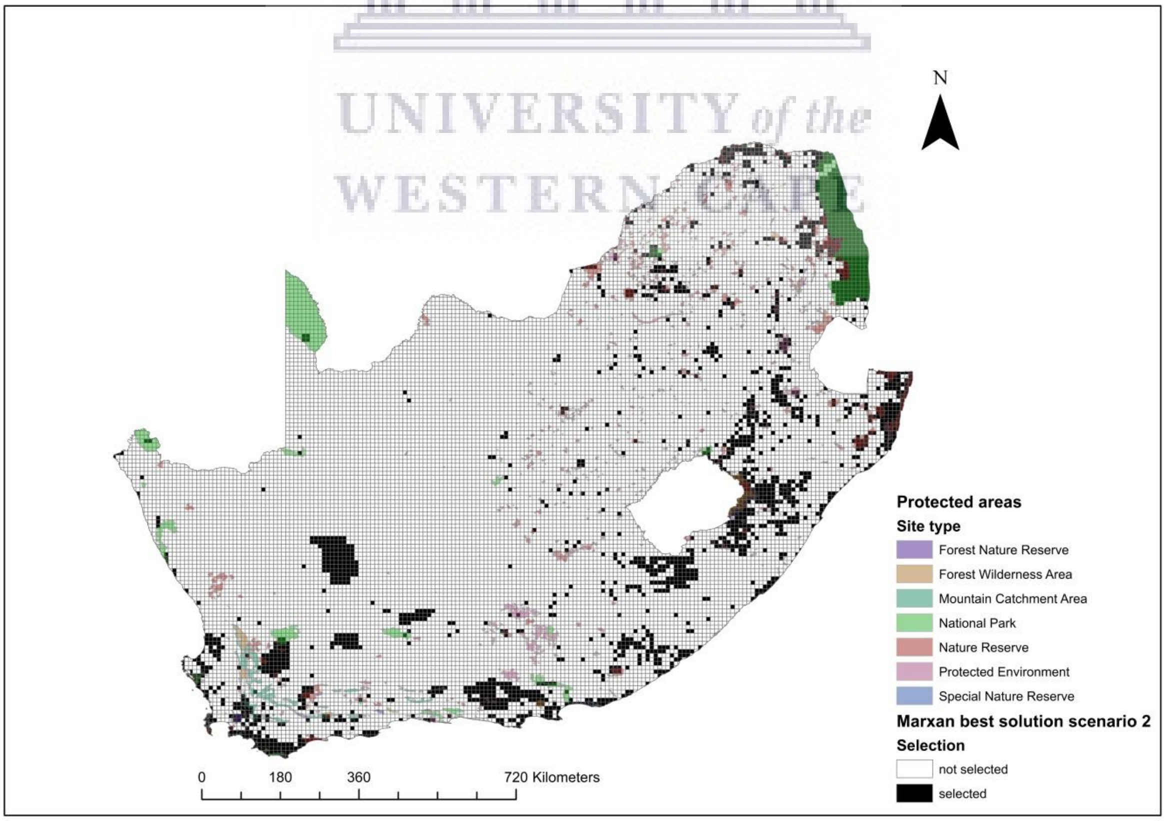

Figure 25: Protected areas (with the specific protected area site type in the legend underneath) spatial association with the Optimum solution (Marxan best solution 2). Planning units in green are those that were not included in the Marxan best solution 2 final reserve network, whereas those in red are those that were included in the Marxan best solution 2 final reserve network.

4.8 Discussion

4.8.1 Marxan cost and landscape analysis

South Africa has a large area of natural landcover across its landscape which means a broader array of areas with high ecological integrity (Cowling et al. 2003). Ecological integrity encompasses the ecosystem's ability to continue on its natural path of evolution and recovery from disturbance over time (Cowling et al. 2003). Many non-natural landcover categories also exist across South Africa's landscape and continue to expandannually. This makes it difficult for conservation planning to establish new reserve networks for conservation (Knight et al.2008; Watson et al. 2010). Non-natural landcover categories include Eskom powerlines and renewable energy industries, and several non-natural land use types such as cultivated land, mining and urban areas. All of the aforementionedwere considered threats to waterbirds and were therefore used in the Marxan cost layer of this study (Taylor et al. 2015).

According to Knight et al. 2008, vulnerability and biological data should be complemented with data such as socio-economic and human capital data to reflect the feasibility and potential effectiveness of conservation actions. After assigning appropriate biodiversity targets according to a species threat status, systematic conservation planning dictates looking for areas that not only have the highest natural integrity, but also are less likely to be influenced by human disturbance (Margules and Pressey 2000). This is exactly what the summed solution of the Marxan best solution scenario 2 showed. The summed solution for the Marxan Best solution scenario 2 in the results section of this Marxan chapter showed that planning unit selection was mostly favoured in provinces containing the lowest costs. However, KwaZulu-Natal was one province that had a high cost and had a high selection frequency according to the summed solution. The location for the planning units in the summed solution was generally found in the eastern and southern areas, away from the dry interior regions, which were very similar to locations of MaxEnt's SDMs. As discussed in chapter 3, these eastern and southern areas contain highly suitable wetland habitat for the ecology of these threatened waterbirds (Siegfried 1967; Taylor et al. 2015).

As noted from the cost values present in all the reserve networks for this study, costs are always present in a reserve network and therefore cannot be avoided when adding planning units for the adequate protection of conservation features (Ardron et al. 2010). There will always be a cost value afforded by any reserve network, when trying to reach conservation targets (Possingham et al. 2006).Marxan is designed to select the reserve network with the least cost possible, subject to the constraints imposed (Game and Grantham 2008). Conservation planning for waterbirds in landscape matrix with growing threats becomes complicated for waterbirds because of their mobile nature and uneven distribution in space (Magris et al. 2014). An ideal scenario for any conservation plan would be a reserve network that consists of the least possible cost with all of the conservation feature targets adequately protected (Ardron et al. 2010). The more planning units that Marxan adds to the final reserve network, the more costly the final reserve network ends up becoming (Game and Grantham 2008).In this study, Marxan designed the Marxan best solution scenario 2 by using a minimal set of sites that represent conservation features at the lowest cost (Game and Grantham 2008).The Marxan best solution scenario 2 possessed the lowest cost value compared to the other four reserve networks. A study by Esselman and Allan 2010 also used Marxan to guide reserve network solutions away from costly planning units, towards planning units with lower costs. As determined earlier on in this chapter, the ideal BLM was calibrated to 0.8 for the Marxan best solution scenario 2. Another study done byHenriqueset al. 2017, also used a relative cost index to biodiversity and the most suitable BLM value, to determine the most suitable selection of planning units for aquaculture management areas.Klein et al. 2014 evaluated the influence of terrestrial protected areas on coral reef condition. In this coral reef condition study, Marxan successfully represented 40% of the distribution of each vegetation type on each island for a minimal cost after calibrating a suitable value for the BLM file.

As initiative that can be implemented for persistence of conservation reserve networks is to encourage the development of strategies as well as monitoring and mitigation efforts that allow waterbirds to better co-exist with these various types of threats (Taylor et al. 2015). Several South African and internationally based strategies, monitoring and mitigation activities are currently in place by various institutions to better allow waterbirds to co-exist with threats such as Eskom powerlines, renewable energy structures and non-natural landcover categories(Department of Environmental Affairs 2016). These strategies and monitoring and mitigation activities will be discussed below.

Most of the South African landscape consists of natural landcover, indicating that the majority of the South African landscape is in good ecological condition (Taylor et al. 2015). The first objective and research question of the Marxan section of this thesis was successfully pursued and answered, respectively. The Spatial national landscape analysis in this chapter's results showed a total length of 383588.32 km² of Eskom powerlines which exists across the South African landscape (Department of Environmental Affairs 2016). Eskom, being responsible for the supply of South Africa's electricity, is in fact, an industry which is expanding on an annual basis (Barnes 2000). This is due to the fact that with a budget of over R300 billion and a growing South African population, the demand for electricity has continued to increase, hence the demand for additional areas of land for powerlines has increased as well (Jenkins et al. 2010). Also, South Africa adopted a National infrastructure plan in 2012, with the aim of transforming the landscape while simultaneously creating jobs and providing better services to the South African population (South African Government 2012). The government invested R827 billion in this project (South African Government 2012). A portion of this investment went to 18 Strategic Integrated Projects (SIPs) (South African Government 2012).

The transport of electricity from the power source (i.e. coal powered plants, renewable energy and nuclear power plants, etc.) to the human population is commonly supplied through above ground powerlines (Jenkins and Joppa 2009). The main physical threat posed by powerlines to waterbirds includes collisions with these powerlines (Janss and Ferrer 2000; Manosa and Real 2001). The construction of powerlines with its complex wiring poses fatal risks to birds such as collisions and electrocutions (Herbert and Reece 1995; Jenkins et al. 2015). Waterbirds, particularly those with large body sizes, often aren't able to manoeuvre their way during flight and end up colliding with powerlines (Taylor et al. 2005). Examples of these large waterbirds include Black Stork, Grey Crowned Crane, African Marsh Harrier and Great White Pelican (Taylor et al. 2005). Several mitigation strategies have been employed in various parts of the world such as North America, Scandinavia, southern Europe and South Africa (Jenkins et al. 2010). These mitigation strategies include using collision and electrocution data from previous years in order to improve the placement of new lines (Jenkins et al. 2010). Secondly, removing the earth wire in powerlines and lastly fitting the wire with brightly coloured aerial marker balls, thickened wire coils and shiny or flapping devices (Jenkins et al. 2010). These approaches employed have been successful for both nocturnal and diurnal species, since it has reduced collision frequencies by at least 50 -60% (Jenkins et al. 2010).

On the other hand, there are also benefits for birds co-existing with powerlines (Catry et al. 2017). Powerlines provide birds a place to perch and thus avoid predators on the ground (Catry et al. 2017). Powerlines have also provided suitable hunting positions for birds of prey to hunt their prey (Kmetova et al. 2012). Lastly, powerlines have provided a location for birds to nest, by providing nesting substrate in sometimes treeless landscapes (Gilmer and Wiehe 1977). These powerlines have also sometimes facilitated the range expansions of several stork species (Gilmer and Wiehe 1977). Despite the progress on monitoring efforts of birds and powerline co-existence, there is still a need for more large-scale cost/benefit applied research which looks at the demographic trade-offs between birds and powerlines (Burgio et al. 2014). This can successfully be achieved through initiating collaborations between scientists, the government and electricity companies that can result in mutual benefit for biodiversity conservation and infrastructure development (Burgio et al. 2014). Monitoring efforts of waterbirds and powerline co-existence is essential for the conservation of waterbirds and their ecology especially since Strategic Integrated Projects (SIPs) 9 and 10 of South Africa's National Infrastructure plan involves expanding on the electricity transmission and network in order to address historical imbalances for the citizens of South Africa (South African Government 2012).

The most common renewable energy types used around the world include hydroelectricity, wind and solar PV (Ellabban et al. 2014).The landscape analysis results for this study show that renewable energy types, including solar PV, wind and solar energy, were the most prevalent renewable energy types present in the South African landscape. With the increase in demand for electricity, wind energy has become a popular industry in South Africa (Jenkins et al. 2015). To minimize habitat fragmentation, the placements of wind farms are recommended to be adjacent to existing disturbed areas (Kiesecker et al. 2011). The lower carbon emissions of wind energy, compared to that of coal fired power plant emissions, render it a more attractive option in terms of its contribution to climate change (Jenkins et al. 2015). Despite its positives, the placement of wind farms not only reduces habitat quality, but a number of waterbird collision-related mortalities have been reported as a consequence (Jenkins et al. 2015). Internationally, many mitigation strategies are currently being tested to reduce the number of avian mortalities induced by wind turbines (Hoover and Morrison 2005). This includes a mitigation strategy that involves temporarily shutting down wind turbines during periods of high bird activity, such as breeding and migration seasons (Hoover and Morrison 2005). Another suggestion was to cluster turbines close together which will encourage flocks to fly around the turbine clusters (Smallwood and Thelander 2004). Increasing the visibility of rotating blades using alternate colours of black and white or ultraviolet paint is another strategy (Hodos et al. 2001). The main goal that all of these mitigation strategies aims to achieve is to find a balance between reducing the effects of bird mortalities from collisions and generating enough wind energy for the human population (Smallwood and Neher 2004). A sound practice for the way forward is to incorporate monitoring at sites and make detailed behavioural observations on bird interactions with existing renewable energy infrastructure (Band et al. 2007). This will assist in the creation of more ideal placements for wind turbines in the future and could minimize the adverse effects it has on birds (Band et al. 2007). Monitoring efforts of the waterbirds and renewable energy co-existence is essential, since SIP 8 of South Africa's National Infrastructure Plan, mentions that the South African economy is in support of green energy initiatives on a national scale (South African Government 2012).

In South Africa, Birdlife South Africa and the Endangered Wildlife Trust have formed a partnership and are continually gathering data on mitigation strategies for the impact of wind energy on birds (Ralston-Paton et al. 2017). Due to the large tracts of lands used by solar PV sources, large tracts of waterbird habitat have been cleared for solar PV plants (Ralston-Paton et al. 2017). Other threats imposed by solar PV plants includemortalities and injuries caused by collisions (Herbet and Reece 1995). Other mortality incidents have also been reported as a consequence of onshore wind facilities (Ralston-Paton et al. 2017). Due to the expanding wind energy industry, scientific monitoring of resident and migrant birds is encouraged and has been initiated at all proposed wind-energy development sites (Jenkins et al. 2015). The Birds and Renewable Energy Specialist Group (BARESG) have developed a set of guidelines and monitoring protocols for assessing wind energy development proposals (Jenkins et al. 2015). The steps of this monitoring protocol include scoping, pre-construction monitoring and impact assessment, construction phase monitoring, and post-construction monitoring (Jenkins et al. 2015). The recommended bird species in this protocol to include are threatened species, rare species, waterbirds and raptors(Jenkins et al. 2015).

The land for cultivation is of importance to the South African population, contributing to the GDP and overall strength of the South African economy (AAS 2002). Each year the agricultural industry contributes billions of Rands to the country's foreign exchange profits (AAS 2002). This industry contributes to the national economy and livelihoods of people via job creation (Poonyth et al. 2002). Certain waterbirds like the Grey Crowned have adapted to cultivated land areas (Pomeroy 1980). Despite using wetland habitat, the Grey Crowned Crane depends on cultivated lands for foraging (Pomeroy 1980). Fifty six percent of Grey Crowned Crane records have been recorded in cultivated lands, of which 7 % were located in maize fields (van Niekerk 2011). Due to the population of people expected to increase in years to come, the cultivation industry will only be intensified (Donald 2004). Studies in Europe have noticed a decline in certain bird populations, with an increase in agricultural intensity (Donald 2004).Some birds such as the Crane species do benefit due to an increase in cultivated areas, which increases their breeding and feeding habitat range (Dauber et al. 2010). However, for most other birds, a cultivated landscape is less suited to their ecology (Dauber et al. 2010). Cultivated vegetation intensification includes factors such as vegetation abundance, diversity and structure (Dauber et al. 2010). These collectively influence ecological factors of species differently and may affect breeding success, feeding and predator avoidance (Dauber et al. 2010). Habitat, crop suitability models and breeding success of waterbird species should be taken into account before using the land for cultivation or intensifying cultivation activity (Brandt and Glemnitz 2014). Studies of cultivation and bird interactions have recommended biodiversity-friendly crops and appropriate crop rotations to be utilized by farmers for agriculture and biodiversity conservation to co-exist (Brandt and Glemnitz 2014). It must be noted that birds are, in fact, needed in cultivated landscapes since certain birds in farmlands are sometimes used to illustrate the condition of biodiversity in cultivated areas (Brandt and Glemnitz 2014)

The mining industry plays a significant role in the South African economy (Delphey and Dinsmore 1993). Mining is of importance to South Africa's economic activity as it contributes to job creation and foreign exchange earnings (Delphey and Dinsmore 1993).Mines, however, reduce water quality for many waterbirds and consequently, range restriction occurs because of reduced habitat availability (Kondolf 1997). Mining is one of the major threats to habitat quality of waterbirds (Scottney et al. 1988). Studies in the Czech Republic have noted that species richness decreased with mine site developments (Lennon et al. 2004). However, some post-mining activities have noted the growth of surrogate habitats that are able to sustain biodiversity, including bird species (Lennon et al. 2004). With the proper management tools after post-mining activities, these sites should be given time to rehabilitate (Salek 2012). One of the common mining processes that should be avoided as much as possible is technical reclamation (Salek 2012). Technical reclamation is a process of replacing soil materials in mining (Salek 2012). Technical reclamation should be avoided as it reduces the natural process like successional stages of ecology from occurring (Salek 2012). Technical reclamation should only be used if the soil becomes toxic or if erosion occurs (Salek 2012).

4.8.2 Marxan analysis

South African conservation plans in the pre-2000 period went through criticism regarding their research implementation gaps (Knight et al. 2006a). Decision making and multi-sectoral planning needed to be approached differently to inform protected area expansion (Knight et al. 2006b). South Africa has made a vast improvement in the implementation of systematic conservation planning (Botts et al. 2019). South Africa is currently a leader in systematic conservation planning, consisting of a community dominated by skilled practitioners, while simultaneously being influenced by academics (Botts et al.2019). This has encouraged practical implementation with a strong sense of scientific rigour in conservation planning across South Africa (Sinclair et al.2018). However, as shown in this thesis, the PAN of South Africa inadequately protects threatened wetland waterbirds. Conversely, the Marxan reserve networks generated for this thesis adequately protects all of the waterbird conservation features. As mentioned in the introduction, good practice for reserve network design requires reserve networks to be Connected, Adequate, Representative and Efficient (CARE principle) (Possingham et al. 2006; Lourival et al. 2009). There were five reserve networks analysed in the results of this thesis, these were namely, the IBAs, formally protected areas, PAN, Marxan best solution 2, and PAN expansion using Marxan. The five reserve networks will now be discussed in terms of its adequate protection for the conservation features as well as its alignment with the CARE principles.

In terms of connectivity, the maps for each of the five reserve networks show a high degree of clustering between the planning units. Planning units that are too small or isolated cannot effectively protect a population of threatened species over a long period of time (Bruner et al. 2001). According to the waterbird distribution and five reserve network maps, the clustering between the planning units for each reserve network seem to be sufficiently connected across the waterbirds' distributions. Connectivity is important as resources are distributed differently across the planning units present in the chains of wetland ecosystems in a country (Ardron et al. 2010). Connectivity across habitats allows different biophysical and chemical processes to co-exist which ultimately ensure that ecological processes function for the existence of waterbirds (Magris et al. 2014). Due to the dynamic mobility of resident wetland organisms, the conservation of chains of wetland ecosystems is crucial for waterbirds to effectively utilise the resources contained within these ecosystems (Runge et al. 2009). Also, different waterbirds have different home ranges as well. For example, the Wattled Crane travels greater distances compared to the Lesser Jacana (Haig et al. 1998). In this specific example, a well-connected reserve network would be an important characteristic for a smaller waterbird such as the Lesser Jacana, which would require a well-connected network of planning units due to its smaller home range (Taylor et al. 2015).

An adequate reserve network is one which contains enough of each conservation feature so that it persists through time (Nel et al 2011; Ardron et al. 2010). Planning for persistence is extremely important for the long-term viability of any population of a species in a reserve system (Cowling et al 2003; Wood et al. 2008). Freshwater ecosystems are interconnected systems and are highly dynamic, therefore including enough of each biodiversity feature is extremely important for its long-term persistence (Ardron et al. 2010). The levels of adequacy are addressed by setting targets per conservation feature as mentioned in the methods (Game and Grantham 2008).

Aim 1 of the Marxan for this thesis as well as objectives and research questions 2, 3, and 4, was about assessing the effectiveness of the current IBAs, protected areas and PANs by ensuring that the conservation features were adequately protected, as well as its alignment with the CARE principles. The IBA, protected areas networks and PAN represented all 10 conservation features. Despite the IBAs, protected areas and PAN representing all of the conservation features, most of these conservation features were not well represented in terms of adequate protection. The protected area network included less than 50% of all the conservation feature targets while the IBAs and PAN included more than 50% of all conservation feature targets in their reserve networks. This is not what was predicted for this thesis, according to prediction 1. A reason why IBAs and the existing protected area networks of South Africa were not adequate reserve networks could more than likely be due to the high targets specified for the conservation features, specifically the modelled conservation features, specified in the spec.dat Marxan input file (Driver et al. 2017).Protected area gap analysis pursued by similar studies had their conservation feature targets set to either 10 or 20% (Watson et al. 2010; Squeo et al. 2012). Though models that are generated by algorithms are extremely useful, it does not fully replicate all the components, stimuli and events of an environment present in the real world (Peterson et al. 2005). It is therefore good practice to set lower conservation targets for any modelled data (Driver et al. 2017).This result of current national protected areas failing to adequately protect conservation features was similar to a study done in Australia (Watson et al. 2010). After assessing the protected areas, it was noted that the protected areas failed to adequately protect 80.4% of the threatened species of Australia (Watson et al. 2010). The average percentage of threatened species geographical ranges that were included in Australia's protected area network appeared relatively high (33.6%). However, of this percentage, only a small number of species, usually those with small geographic ranges, were actually represented in Australia's protected area network. (Watson et al. 2010). A total of 12 Critically Endangered species and 154 Vulnerable and Endangered species were not represented in the protected areas (Watson et al. 2010). Marxan was also one of the decision-support tools for rezoning the Great Barrier Reef (Ball et al. 2009). Before 2004, the Great Barrier Reef had 5% of its extent in no-fishing zones. Marxan managed to successfully rezone the percentage of the Marine park in no-take fishing zones from 5% to 33%, and the target for most conservation feature targets of 20% was met (Ball et al. 2009).

Despite this Marxan analysis showing the IBAs, protected area networks and PAN of South Africa falling short for the adequate protection of the conservation targets, South Africa has made progress in representing more ecosystems and ecological processes using the National Protected Area Expansion Strategy (NPAES) (Department of Environmental affairs 2016). The NPAES uses species in prioritisation of the targets which are ecosystem based (Department of Environmental affairs 2016). As mentioned earlier in this study, species data are included >80% of the time (Botts et al. 2019). Comprehensive national targets have been set for the prioritisation and planning of wetlands, rivers, estuaries and many other ecosystems (Department of Environmental affairs 2016). Inland aquatic ecosystems are currently poorly represented in the current protected area network, with many of these ecosystem types being in poor ecological condition (Skowno et al. 2019) A total of 2352km^2 of wetland habitats currently requires protection for this conservation target to be adequately met within the next 20 years (Department of Environmental affairs 2016).

For aim 2, research question and objective 5 and 6, an effective Marxan network for the 10 conservation features was to be designed and aligned with the CARE principles (Possingham et al. 2006). The Marxan best solution 2 and PAN expansion (as per objectives and research questions 5 and 6), were, in fact, the only 2 networks that not only represented all of the conservation features, but also adequately protected all of the conservation features in their reserve networks. Prediction 2 for the Marxan analysis was therefore correct. This result was similar to a protected area gap analysis done in Chile (Squeo et al. 2012). A Marxan analysis indicated that Chiles's terrestrial protected areas did not adequately protect ecosystems and species (Squeo et al. 2012). The best solution generated by Marxan for the Chile protected area gap analysis adequately met the target of 10% for conservation features (Squeo et al. 2012).

In terms of representivity for the CARE principle, all 5 reserves successfully represented all of the conservation features in their reserve networks. Globally, governments have agreed to establish protected area systems that contain viable representations of every terrestrial, freshwater and marine ecosystem (IUCN 2003). By placing each conservation feature in several protected areas, it ensures that there is a representative sample of each conservation feature present in different habitats across the planning units of a study area (Game et al. 2008). Disturbance, catastrophes, or any land-use changes can be unpredictable in where exactly it will occur (Game et al. 2008). Representivity in this way prevents the entire population of a conservation feature from completely disappearing in one catastrophic event (Ardron et al. 2010; Department of Environmental Affairs 2016). A study of freshwater ecosystems in South Africa noted that 50% of rivers found in protected areas are intact and only 28% of rivers located outside of protected areas are intact. This emphasizes the important role protected areas can play in conserving a representation of conservation features such as freshwater ecosystems and associated biodiversity (Nel et al. 2009b).

The letter E is the last letter of the CARE principal, which denotes efficiency (Ardron et al. 2010). An efficient reserve network is also interpreted as a cost-effective reserve network and is also a reserve network that is connected, adequate and representative (Ball et al. 2009). Marxan successfully generated a best solution network configuration protecting all 10 waterbirds. Out of the 5 reserve networks, the two reserve networks generated using Marxan, namely the Marxan Best solution scenario 2 and PAN expansion, aligned most closely to the "CARE" principles, as opposed to the other three reserve networks. As mentioned in the results, the BLM value of 0.8 was calibrated for the Marxan Best solution scenario 2 network.As mentioned in the calibration section of this chaper, the BLM was unsuccessfully calibrated for the PAN expansion strategy with the following error message appearing in Marxans output_log.dat file, “Warning: Connection File boundary.dat not found 0 connections entered”. After much extensive research, a solution to this problem was unfortunately not found. On the other hand, the successful calibration and inclusion of the 0.8 BLM value for Marxan Best solution scenario 2 network ensured that it was compact, and contained the optimum amount of clustering between planning units (Game and Grantham 2008). Since space is a limited resource for conservation planning, the clustering of planning units in compact reserve networks makes compactness an important characteristic for good reserve network design (Possingham et al. 2002). The collection of planning units in these two Marxan solutions, showed Marxan’s ability in adding a set of complementary planning units to meet the defined target for the biodiversity features (Game and Grantham 2008). The first part of the hypothesis for this chapter was therefore accepted. Marxan’s functioning of simulating annealing using iterative improvement over a user defined cost surface allows it to generate the best complementary set of planning units through several repeated runs at minimal cost for the Marxan best solution 2 and PAN expansion (Game and Grantham 2008). The iterative improvement algorithm added planning units for the final reserve network to adequately meet the conservation targets at the expense of increased cost assigned for every planning unit added to the final reserve network (Game and Grantham 2008). This is why the Marxan best solution 2 and PAN expansion were able to meet all the conservation targets, and the Marxan best solution having the lowest total cost (Ardron et al. 2010). The IBAs, protected areas and PANs are existing networks that were assessed and not created from conception (BirdLife International 2004; Department of Environmental Affairs 2016).

Marxan’s ability to include complementary planning units is based on the systematic conservation planning principle, which is to create a network design with complementary planning units (Ardron et al. 2008). As noted from the results, the area of the current PAN would need to be increased by more than 50% in order to adequately protect the 10 threatened waterbird species. The additional amount of planning units added to the existing network shows Marxan’s ability to add complementary planning units in order to include all biodiversity features in the final reserve network using the user defined target (Game and Grantham 2008). A similar study done in Australia assessed the country’s protected area network on how well it adequately protects the country’s threatened biodiversity (Watson et al. 2010). It was noted that existing protected areas would need to be increased by 17.8% in order to adequately protected Australia’s threatened species (Watson et al. 2010). The percentage increase needed for adequate threatened species protection in the

Australian study is far lower compared to the percentage increase needed for the adequate protection of threatened species using the protected area expansion in this thesis. A reason for this “land-hungry” PAN expansion solution generated from Marxan for this thesis could be because of the BLM that was not calibrated successfully. Using a BLM reduces the total boundary of a solution (Ardron et al. 2010). Since the boundaries are shared between adjacent or connected planning units, it encourages clustering and compactness in the final network reserve solutions (Ardron et al. 2010). As mentioned in the calibration section of this chapter, 1 million to 1 billion iterations were tested but this made no difference to the “land hungry”result and the unusual selection of planning units in the Northern Cape.

As noted in the results, the Marxan best solution scenario 2 hadseveral areas of key IBAs and protected areas in its network. In terms of area (km^2), the Kruger National Park and adjacent areas was the most dominant IBA category present in the Marxan best solution scenario 2. Nature reserves were the most dominant protected area category present in the Marxan best solution 2. The second part of the hypothesis for chapter 4 was therefore accepted. Having key IBAs intersecting with the Marxan Best solution 2 is of great value to several of the 10 threatened waterbird conservation features ecology studied in this thesis (Taylor et al. 2015). Due to their distribution in the KZN region, some waterbirds, namely the Saddle Billed Stork and Lesser Jacana are mainly restricted to protected areas and IBA’s such as Ndumo and Mkuze Game reserves and iSimangaliso Wetland Park (Taylor et al. 2015).

iSimangaliso Wetland Park is an example of an IBA that contains several important feeding and breeding habitats for various waterbirds (Taylor et al. 2015). The establishment of the 332000-ha iSimangaliso Wetland Park has greatly benefited both the Lesser Jacana and African Pygmy Geese, with the Lesser Jacana being included as a key species in the KZN systematic conservation plan (Taylor et al. 2015). Vast majorities of Wattled Crane populations occur in the KZN Midlands (McCann et al. 2000). Large numbers of Grey Crowned Crane individuals occur across northern KwaZulu-Natal and Eastern Cape, which are areas of suitable breeding and feeding habitat for this species (Morrison and Bothma 1998). Close to 100 populations of Saddle Billed Storks rely exclusively on the Kruger National Park (Taylor et al.2015). Saddle Billed Storks tend to be very localised and strongly dependent on protected areas and IBAs such as the Ndumo Game reserve, iSimangaliso Wetland Park and Mkuze Game reserve (Taylor et al. 2015). Additionally, Northern KZN and iSimangaliso Wetland Park are also two important breeding grounds for the Yellow Billed Stork species (del Hoyo et al. 1996).

Maputaland in Kwa-Zulu Natal and the Nyl Floodplain are important foraging and breeding grounds for the African Pygmy Goose (Tarboton 2001). iSimangaliso in Kwa-Zulu Natal is the prime habitat for the Lesser Jacana, where a calculation of 22 birds/ 100 ha were assessed to be present (Taylor et al.2015). The Lesser Jacana also sometimes depends on Nyl Floodplain in wet years (Tarboton and Fry 1986). Dassen and Vondeling Islands and iSimangaliso in KZN are the three key sites for Great White Pelican breeding (Crawford et al. 1995). Pink Backed Pelicans depends on various sites like iSimangaliso and Pongola river floodplain for feeding. This species breeds in areas close to Richards Bay (Bowker et al. 2010). Between 10 - 20 breeding pairs of Black Stork were recorded in KZN in 2015 (Taylor et al. 2015). Isolated breeding populations have also been found in Waterberg, Soutspanberg and Magaliesberg (Siegfried 1967). Species such as the Great White Pelican and Pink Backed Pelican depend on the water levels of saline waterbodies, such as lagoons and estuaries for feeding and to initiate their breeding cycle eg. Great White Pelican at the IBA, Lake St Lucia (Bowker and Downs 2012).

The Marxan best solution 2 aligned more closely to the CARE principle of systematic conservation planning than the 4 other reserve networks. The hypothesis for chapter 4 of this thesis was therefore accepted. As per objective and research question number 6, the PAN expansion strategy was a reserve system that also aligned close to the CARE principle due to its ability to adequately protect all 10 waterbirds. However its area size (km^2) and cost was far too large. As mentioned earlier in this discussion, some of its planning units were located in arid inland regions such as the Northern Cape, which is highly unsuitable for waterbird ecology (Taylor et al. 2015). Due to the intersection of Marxan's best solution scenario 2 with several key IBAs and protected areas, this Marxan reserve network should not be considered as the best solution, but rather its planning units should be seen as possessing potential value which can be used to complement the existing IBA and protected area networks. Aim 3 of this study was successfully pursued and prediction number 3 for the Marxan section of this study was therefore correct. Objective 7 and Aim 3 were successfully pursued and research question number 7 was successfully answered. A study done in the Iberian Peninsula found complementary sets of priority areas using Marxan for freshwater biodiversity conservation opportunities (Yu-Pin et al. 2014). The objective of the study done by Yu-Pin et al. 2014 was also to select a set of additional areas at minimal cost for the adequate representation of freshwater biodiversity. The addition of these planning units from the Marxan best solution scenario 2 can therefore complement the existing IBA and protected areas and possibly assist these networks in better achieving the targets of the threatened waterbirds (Ardron et al. 2010). Although the Marxan best solution scenario 2 supported the hypothesis by showing that it adequately protected all the conservation targets and aligned with the CARE principles, the planning units of the Marxan best solution scenario 2 should *not* be seen as the only solution. The Marxan best solution scenario 2 is hypothetical and represents what could have been achieved in terms of efficiency for a group of conservation features (Ardron et al. 2010). If the BLM was successfully calibrated for the PAN expansion in this study, it would have created a more efficient reserve network because it takes existing conservation efforts into consideration and would have been smaller and less costly(Game and Grantham 2008; Ardron et al. 2010; Yu-Pin et al. 2014).The study done in the Iberian Peninsula (Yu-Pin et al. 2014), showed the possibility of its planning units complementing the existing IBA and protected area networks. Using Marxan to expand upon the existing protection efforts could therefore have created a more realistic reserve network while possibly also protecting all of the conservation feature targets of the 10 waterbird species (Game and Grantham 2008; Ardron et al. 2010).

In the past, the spatial designs for South Africa's formally protected areas were designed around economic reasons such as tourism and not for the inclusion of biodiversity distribution (Department of Environmental Affairs 2016). In previous years, protected areas were designed without a systematic conservation planning approach (Jantke and Schneider 2010). According to the National Protected Area Strategy of 2016, protected area design had been biased towards areas set aside for indigenous forests, the Lowveld, fynbos and savannah biomes (Department of Environmental Affairs 2016). In the last decade however, South Africa has made progress in systematic conservation planning by adopting a more practical approach to implementing conservation planning in the real world (Botts et al. 2019). This practical implementation of conservation planning in the real world has been successful due to sharing and processing throughout the academic, practitioner and government institutions (Radeloff et al. 2013). For the practice of systematic conservation planning in future, a relationship between scientists and practioners is required to consistently build capacity within agencies and legislative processes(Botts et al. 2019).

Although this thesis used species as conservation features, several studies have noted coarse filtered conservationfeaturessuch as freshwater ecosystems, to be poorly represented (Nel et al. 2007). As a signatory of the Convention of Biological Diversity, South Africa has agreed to achieve a measurable set of targets within a 20-year period, using strategic planning mechanisms (Department of Environmental Affairs 2016). These targets are referred to as the Aichi targets (Department of Environmental Affairs 2016). In order to meet the protected area Aichi target, a total area of 413163 km^2 needs to be added to South Africa's formally protected area network, of which 211896km^2should be Marine benthic and coastal ecosystems (Department of Environmental Affairs

2016). Within the next 20 years, South Africa aims to protect 2352 km^2 of wetlands (Department of Environmental Affairs 2016).

4.9 Conclusion

In a dynamic landscape with conflicting land-use interests among various sectors, designing an efficient conservation plan provides a good understanding of management between all sectors of land-use (Driver et al. 2017). Vulnerability and biological data should be complemented with relative threat data such as socio-economic and human capital data to reflect the feasibility and potential effectiveness of conservation actions (Knight et al. 2008). Expanding requirements for Eskom powerlines and the growth of the renewable energy industry presents the possibility of an increase in non-natural land cover (Jenkins et al. 2010). There are several conservation initiatives that are in place for the several waterbird species by organizations like Birdlife, EWT, and Eskom etc. (Taylor et al. 2015). All of these initiatives currently contribute to good management and mitigation strategies for the conservation of these waterbirds within the growing Eskom powerline and renewable energy industries (Taylor et al. 2015). Non-natural landcover such as cultivation and mining, are particularly important to the human population of South Africa (South African Government 2012). Fortunately, there are several monitoring and mitigation strategies that exist and are being practiced regarding any changes made across the South African landscape (Lennon et al. 2004; Brandt and Glemnitz 2014;Burgio et al. 2014). Determining which areas to protect and how to prioritize management actions in space can be complicated (Pressey 2004). Good practice guidelines provided by the "CARE" principle used in systematic conservation planning has allowed conservation planning to become more manageable and allowed more explicit decisions relating to land-use to be made (Ardron et al. 2010; Botts et al. 2019). With a decline in range extensions of waterbirds due to a decline in wetland habitat quantity and quality, my research identified the need for 10 threatened wetland-dependent waterbirds to be included in a conservation plan (Taylor et al. 2015). Inland aquatic ecosystems are currently poorly represented in the current protected area network, with many of these ecosystem types being in poor ecological condition (Skowno et al. 2019). A total of 2352km^2 of wetland habitat currently requires protection for this conservation target to be adequately met, within the next 20 years (Department of Environmental Affairs 2016). After assessing the current IBAs, protected areas and PANs, the maps from the Marxan assessment showed that these reserve networks were well connected. However, these reserve networks did not represent the 10 waterbird conservation features adequately enough (with respect to the CARE principle). A reason for this could be that the targets for the conservation features, especially the modelled conservation features, in Marxan were set too high (Driver et al. 2017). For future protected area expansion approaches, targets should not be set high for the conservation features, especially those that are modelled (Driver et al. 2017). The Marxan protected area gap analysis done in Chile and Australia are good examples of setting lower targets to achieve conservation feature targets at minimal cost (Watson et al. 2010; Squeo et al. 2012). These two studies had set a target of 10 or 20 to adequately protect all of the conservation features defined in their study at minimal cost (Watson et al. 2010; Squeo et al. 2012). Expanding on the current PANs in this study resulted in a reserve network that was costly and too "land-hungry", as it included areas in the arid inland areas such as the Northern Cape to adequately protect all the conservation features. After comparing the sizes of the current PAN and the PAN expansion, it was noted that the current PAN would need to be increased by more than 50% in order to adequately protect all of the conservation features. The Marxan best solution scenario 2 contained all the CARE principles of systematic conservation planning and adequately protected all of the conservation features. The Marxan best solution scenario 2 also had the lowest cost which is paramount for the functioning and persistence of waterbird ecology (Taylor et al. 2015). The Marxan analysis also noted that the Marxan best solution scenario 2 consisted of several important Key IBAs and protected areas beneficial for waterbird feeding and breeding ecology (Taylor et al. 2015). The most efficient solution going forward for the representation, functioning and persistence of waterbird ecology would be to generate a PAN expansion strategy after successfully calibrating a suitable BLM. This network takes into account the existing conservation efforts whereas a Marxan solution is hypothetical and represents what could have been achieved in terms of efficiency for a group of conservation features (Game and Grantham 2008; Ardron et al. 2010; Yu-Pin et al. 2014).

Habitats such as wetland ecosystems could also have been listed as conservation features in Marxan, with the appropriate targets assigned for future reserve network planning for these waterbird species in this study (Ardron et al. 2010). This study could therefore be further improved by conducting a Marxan assessment for wetland and river ecosystem types, as these are important habitats for the 10 conservation features used in this study. After running these ecosystem conservation features together with the 10 waterbird conservation features in Marxan, the priority sites generated could be assessed as complementary planning units to the IBA and formally protected area networks. Additionally, national threat data such as water and air pollution and invasive species spatial data would be valuable to future national systematic conservation planning analyses for the 10 threatened freshwater wetland waterbirds. Unfortunately, this GIS data is currently not available (Taylor et al. 2015).

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6 Appendix: Additional MaxEnt Results

Table 22: Training AUC gain of environmental variables for each waterbird

Training AUC gain with only the variable	African Marsh Harrier	African Pygmy Goose	Black Stork	Great White Pelican	Great crowned crane	Lesser Jacana	Saddle Billed Stork	Pink Backed Pelican	Wattled Crane	Yellow Billed Stork
Bio1	0.0606	1.0464	0.0936	0.318	0.6538	0.8451	1.6325	0.6786	1.6932	0.2177
Bio2	0.5121	0.9402	0.1193	1.3743	0.37	1.0257	0.6489	0.737	0.7689	0.3404
Bio3	0.0203	0.2636	0.0153	0.4732	0.057	0.3347	0.3948	0.0975	0.0007	0.0069
Bio4	0.488	1.5512	0.2274	0.7256	0.5298	1.6892	1.3984	0.9483	0.8333	0.2218
Bio5	0.3092	0.0066	0.0041	0.0651	0.9282	0.0018	0.1928	0.001	1.9728	0.0022
Bio6	0.2036	1.3096	0.1241	1.5802	0.2187	1.2533	1.5004	0.888	0.739	0.2026
Bio7	0.5293	1.0606	0.174	1.3188	0.4898	1.1626	0.9974	0.6904	0.7957	0.25
Bio8	0.1868	0.0941	0.0032	0.0458	0.9276	0.0437	0.3146	0.0625	2.1063	0.0139
Bio9	0.0342	1.5034	0.1495	0.5425	0.3353	1.3816	1.836	1.0048	1.0345	0.2975
Bio10	0.2228	0.0886	0.0015	0.0256	0.9943	0.0305	0.4325	0.0539	2.1326	0.0273
Bio11	0.048	1.4898	0.1716	0.6813	0.2926	1.3797	1.94	1.027	0.9718	0.3185
Bio12	0.3613	2.1615	0.2329	0.514	0.2699	2.2924	1.739	1.5514	0.3352	0.448
Bio13	0.2923	1.9723	0.2372	0.1248	0.403	2.0462	1.8887	1.4117	0.5017	0.5335
Bio14	0.3178	1.6439	0.1495	1.6594	0.0132	1.7239	1.1891	1.1714	0.0426	0.1671
Bio15	0.095	1.0476	0.2309	0.3921	0.5511	1.0854	1.8566	0.7656	0.6909	0.5588
Bio16	0.325	2.0588	0.2353	0.1795	0.4075	2.1627	1.8106	1.4223	0.5141	0.5112
Bio17	0.3306	1.838	0.1688	1.5552	0.0316	1.9397	1.3411	1.3489	0.0443	0.2332
Bio18	0.3455	1.8506	0.1954	0.2203	0.4321	1.9525	1.4351	1.3329	0.4804	0.4549
Bio19	0.3164	1.9025	0.1753	1.411	0.029	1.9979	1.4232	1.3842	0.0309	0.2619
Vegetation	0.478	1.0442	0.1089	1.2174	0.6538	0.99	0.8754	0.8514	0.9157	0.3496

Table 23: Training AUC gain of environmental variables for each waterbird.

Test AUC with only the variable	African Marsh Harrier	African Pygmy Goose	Black Stork	Great White Pelican	Great crowned crane	Lesser Jacana	Saddle Billed Stork	Pink Backed Pelican	Wattled Crane	Yellow Billed Stork
Bio1	0.5891	0.8343	0.6223	0.7315	0.8157	0.8353	0.913	0.7954	0.936	0.65
Bio2	0.7864	0.9039	0.6694	0.9009	0.7574	0.9092	0.8443	0.8563	0.8598	0.7454
Bio3	0.518	0.7276	0.5721	0.6698	0.5978	0.7471	0.7706	0.6221	0.4902	0.5383
Bio4	0.7685	0.9209	0.7046	0.8208	0.7723	0.9336	0.9191	0.83	0.8579	0.6891
Bio5	0.7016	0.5182	0.5295	0.5791	0.867	0.4539	0.6647	0.4969	0.9585	0.5761
Bio6	0.6515	0.8976	0.6286	0.9183	0.679	0.8764	0.9175	0.8151	0.8024	0.65
Bio7	0.7924	0.9106	0.6915	0.8922	0.7861	0.9172	0.8876	0.8404	0.8591	0.7216
Bio8	0.6477	0.6422	0.5147	0.5914	0.8622	0.6317	0.7297	0.6405	0.9621	0.5418
Bio9	0.5897	0.8868	0.6564	0.802	0.7368	0.8764	0.9356	0.8195	0.8601	0.6649
Bio10	0.6716	0.6412	0.5126	0.5979	0.8719	0.6134	0.749	0.6292	0.9623	0.5562
Bio11	0.6144	0.8914	0.6588	0.8367	0.7172	0.8763	0.9409	0.8232	0.8495	0.6679
Bio12	0.737	0.954	0.6915	0.7863	0.709	0.9535	0.9402	0.8824	0.7735	0.761
Bio13	0.7011	0.9525	0.6868	0.6475	0.7391	0.9539	0.9435	0.8909	0.7992	0.7817
Bio14	0.7198	0.9209	0.6637	0.9253	0.5535	0.9178	0.8942	0.8345	0.5662	0.6683
Bio15	0.5973	0.8751	0.669	0.7843	0.8038	0.872	0.9454	0.8219	0.7995	0.7861
Bio16	0.7053	0.9566	0.6894	0.6808	0.7411	0.9581	0.9408	0.8884	0.8059	0.7768
Bio17	0.7337	0.9299	0.672	0.9193	0.5884	0.9273	0.909	0.8461	0.6656	0.6936
Bio18	0.7272	0.9434	0.685	0.675	0.7495	0.9443	0.9245	0.8801	0.7889	0.7669
Bio19	0.7334	0.9353	0.6686	0.9099	0.5874	0.9312	0.917	0.8507	0.6585	0.7068
Vegetation	0.7572	0.8628	0.6209	0.8729	0.7909	0.8528	0.8217	0.8343	0.8498	0.7107

African Marsh Harrier

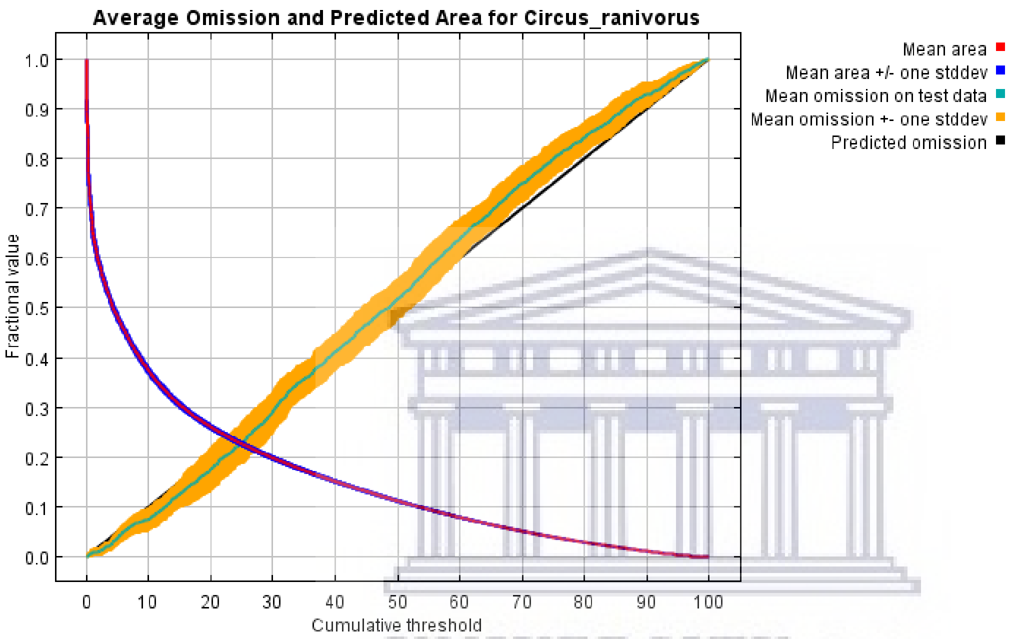

Figure 26: Average Omission and Predicted area for the African Marsh Harrier

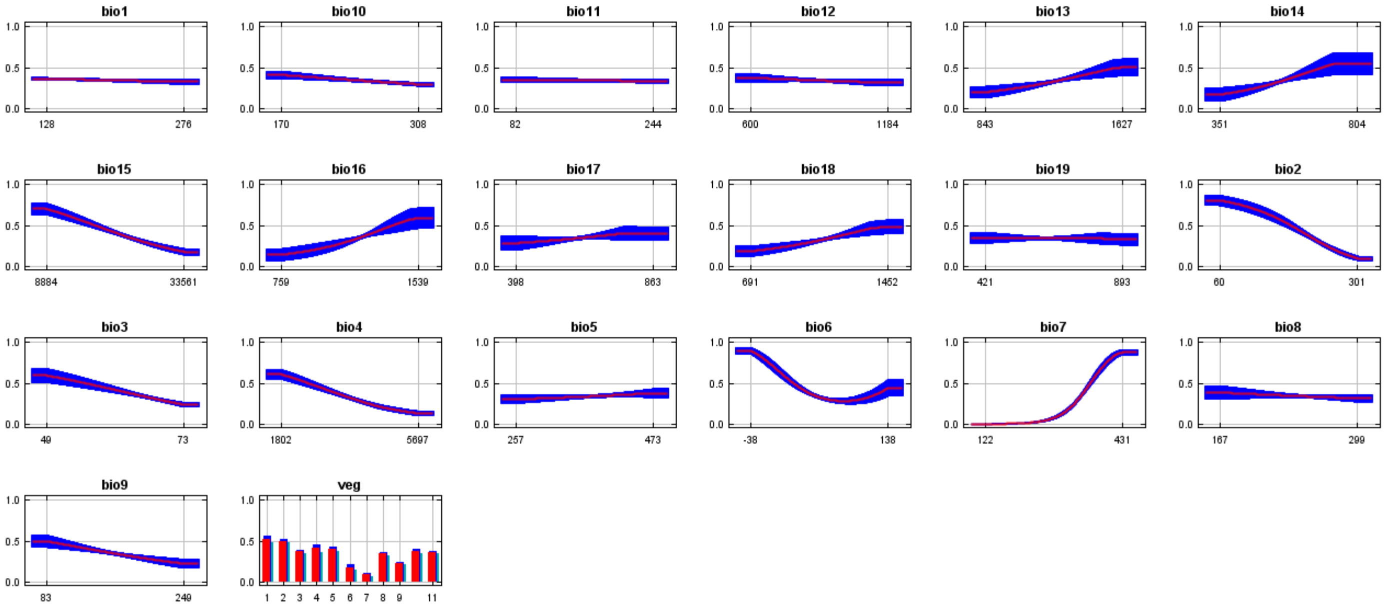

Figure 27: Marginal response curves for the African Marsh Harrier

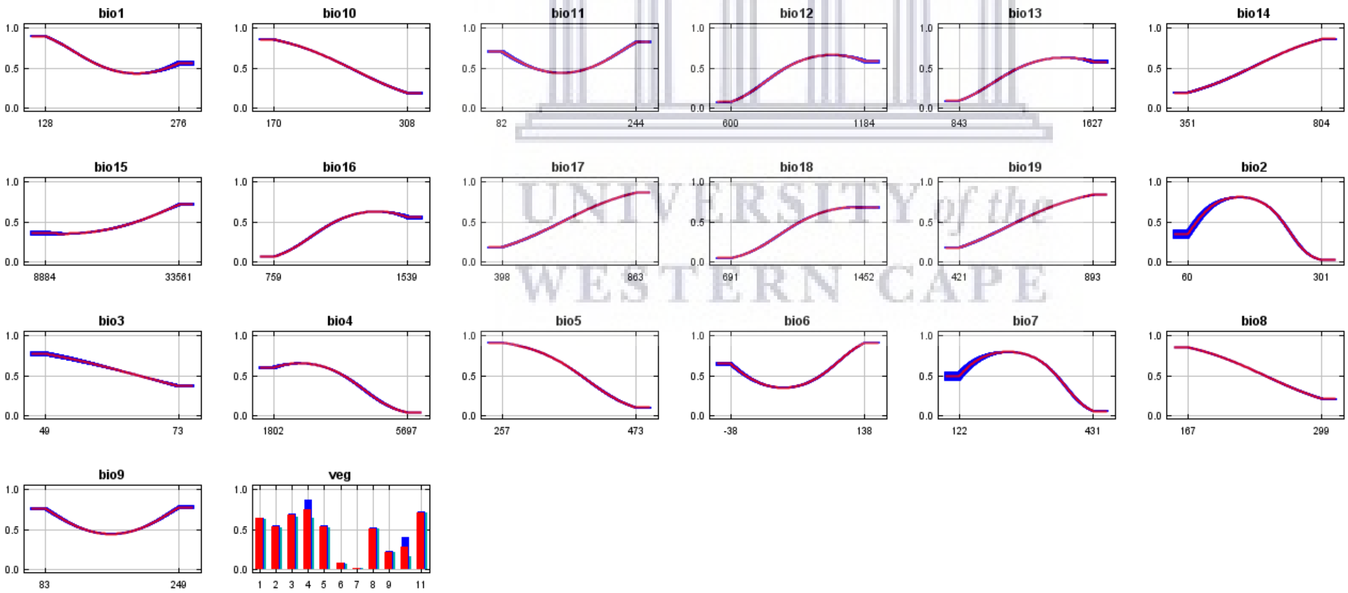

Figure 28: Alternative response curves for the African Marsh Harrier

Table 24: Analysis of variable contribution for the African Marsh Harrier

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Variable	Percent contribution	Permutation importance
veg	41.1	12
bio4	20.3	8
bio7	8.4	6.1
bio19	3.4	0.6
bio5	3.3	0.2
bio2	2.5	9.8
bio10	2.5	0.2
bio14	2.4	9.2
bio6	2.4	12.7
bio12	1.9	0.3
bio8	1.5	0.4
bio17	1.5	2.1
bio1	1.5	0
bio3	1.3	2
bio9	1.2	2
bio13	1.1	5.1
bio15	1.1	13.5
bio16	1.1	11.6
bio18	0.9	4
bio11	0.3	0

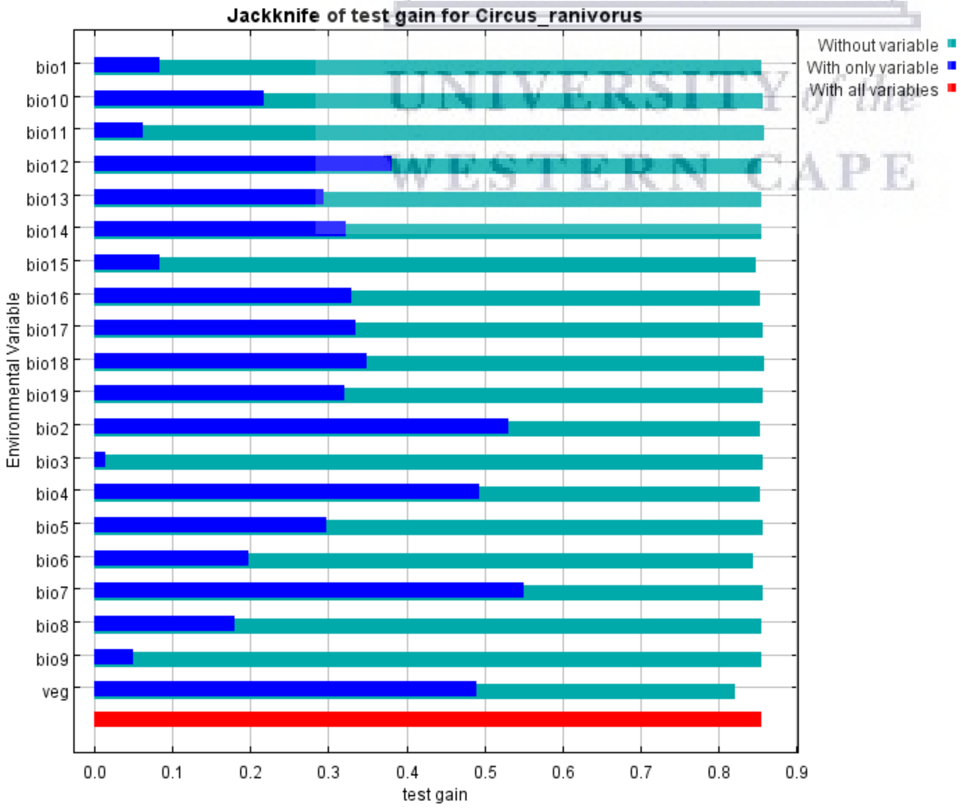

Figure 29: Jackknife of regularized training gain for the African Marsh Harrier

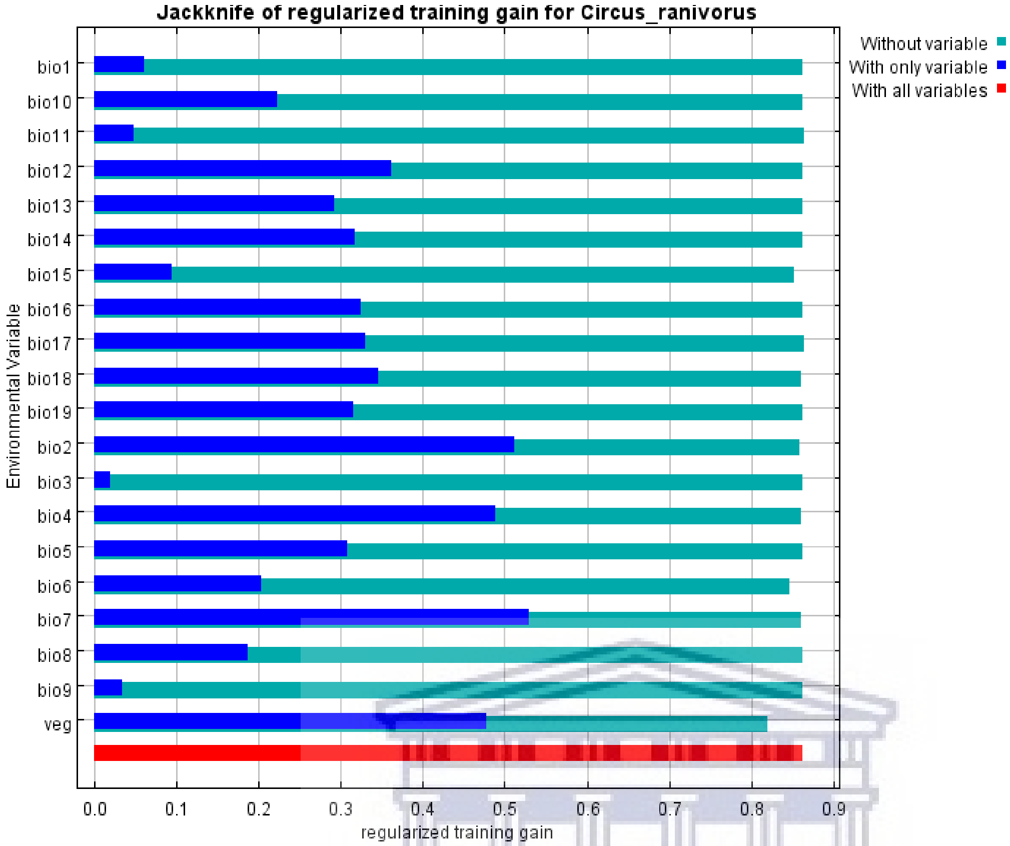

Figure 30: Jackknife of test gain for African Marsh Harrier

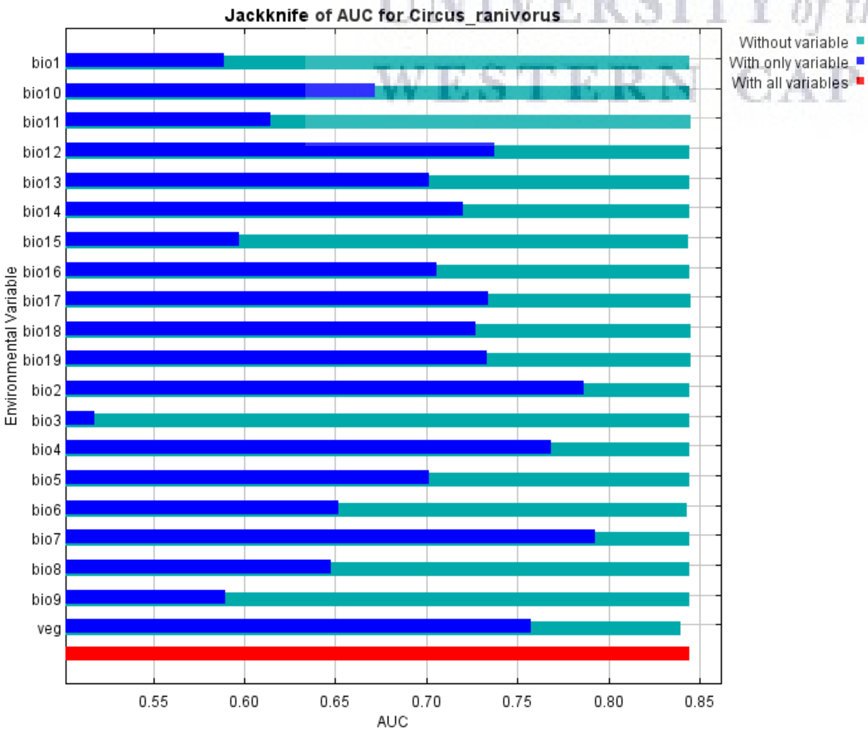

Figure 31: Jackknife of AUC for the African Marsh Harrier

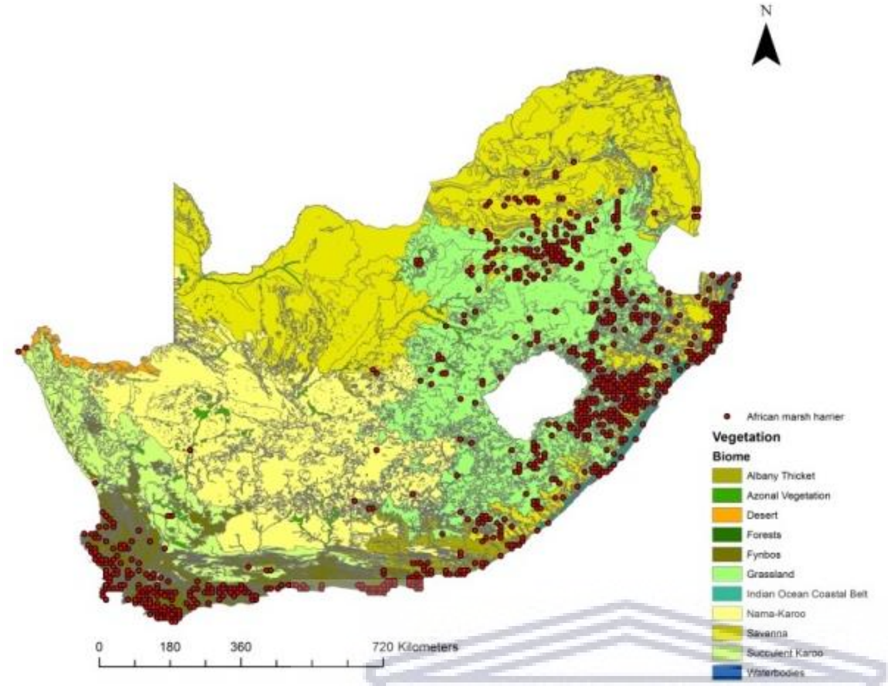

Figure 32: African Marsh Harrier point distributions across the 11 vegetation biomes

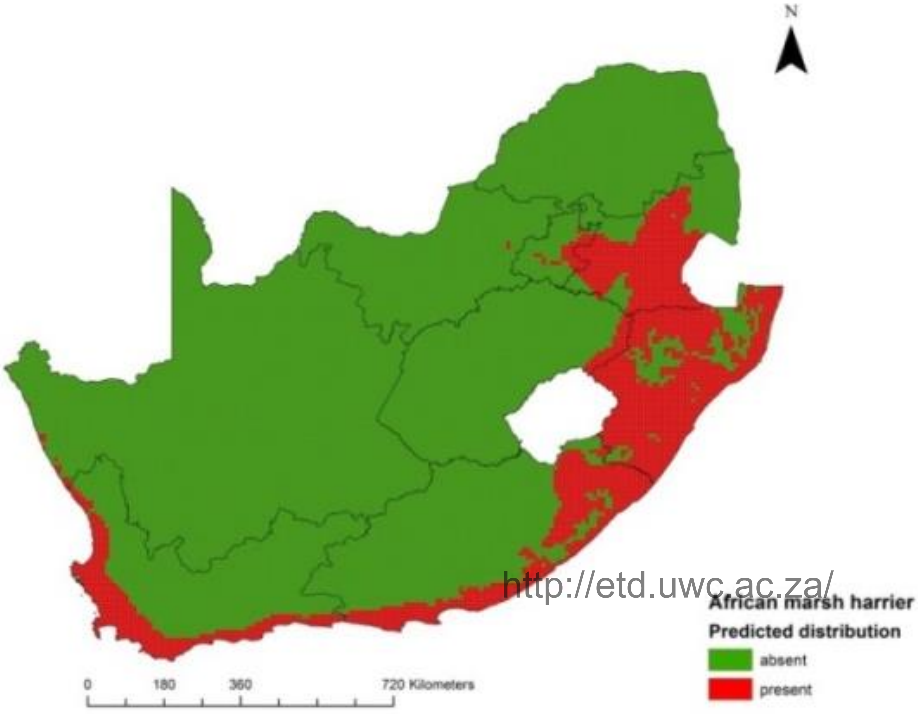

Figure 33: The three most important biomes for the African Marsh Harrier according to MaxEnt

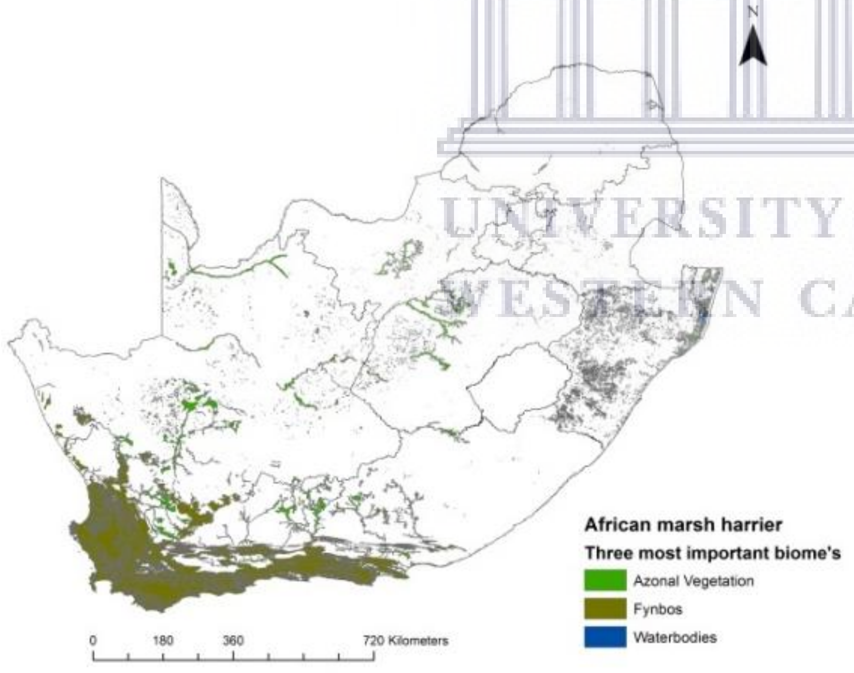

Figure 34: Predicted areas of presence according to MaxEnt for the African Marsh Harrier

African Pygmy Goose

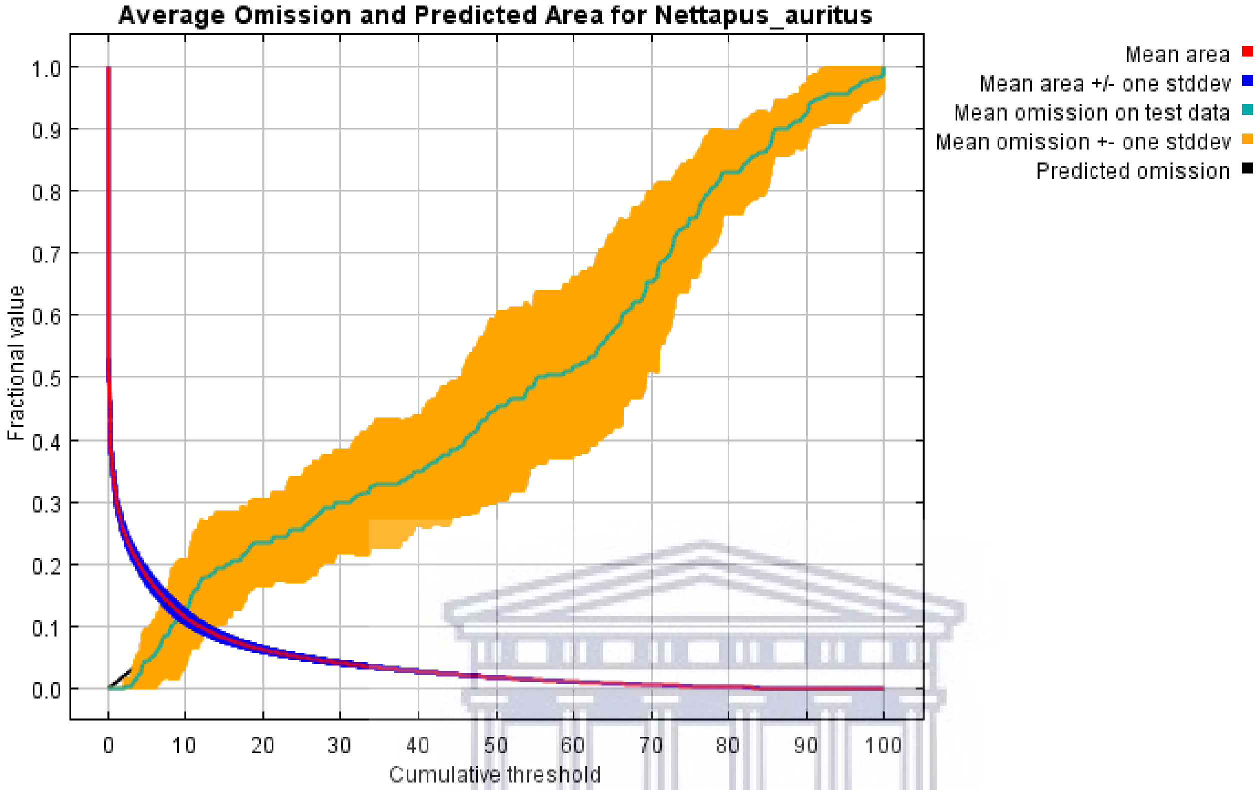

Figure 35: Average Omission and Predicted area for the African Pygmy Goose

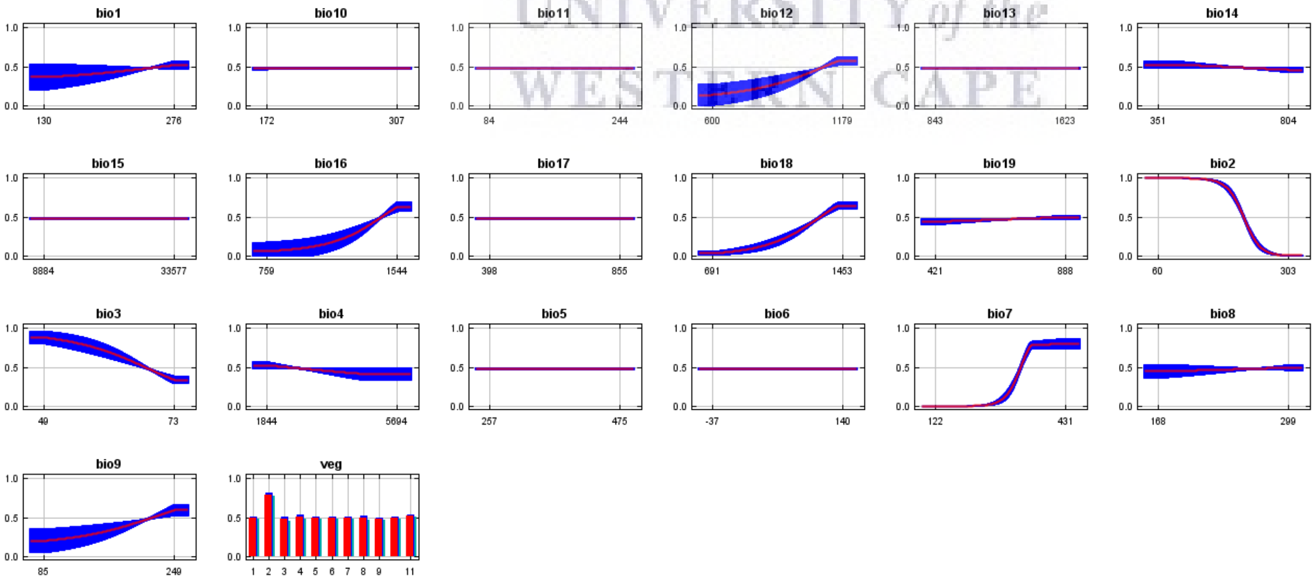

Figure 36: Marginal response curves for the African Pygmy Goose

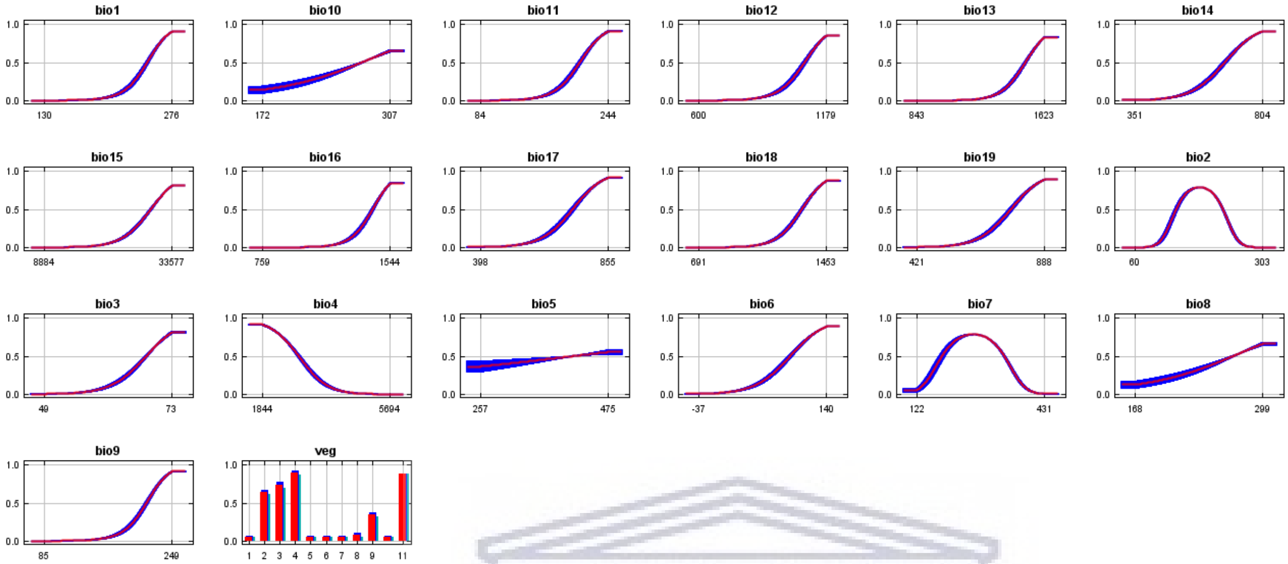

Figure 37: Alternative response curves for the African Pygmy Goose

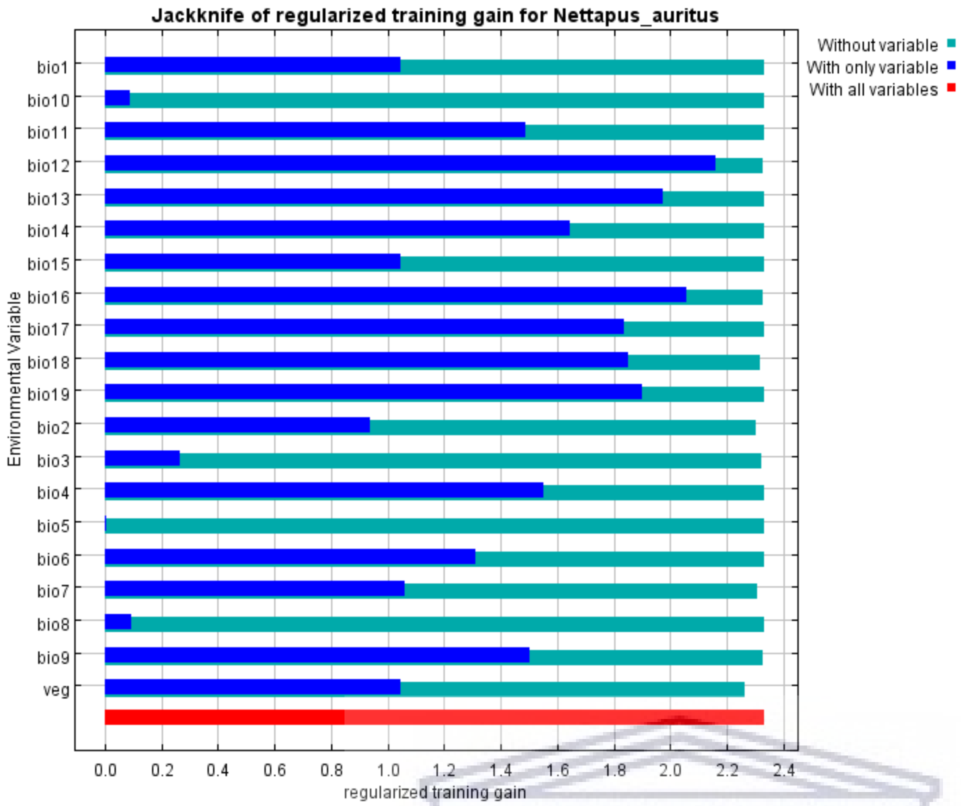

Figure 38: Jackknife of regularized training gain for the African Pygmy Goose

Table 25: Analysis of variable contribution for the African Pygmy Goose

Variable	Percent contribution	Permutation importance
bio12	32.7	9.5
bio16	22.2	27.1
bio13	9.4	0
bio17	8	0
bio19	7.2	0.1
bio14	3.7	0
veg	3.1	1
bio3	2.9	1.6
bio18	2.6	9
bio15	2.1	0
bio11	1.3	0
bio6	1.2	0
bio9	1.1	3
bio8	0.5	0.1
bio5	0.5	0
bio2	0.4	33.5
bio10	0.4	0
bio7	0.3	14.7
bio4	0.2	0
bio1	0.2	0.5

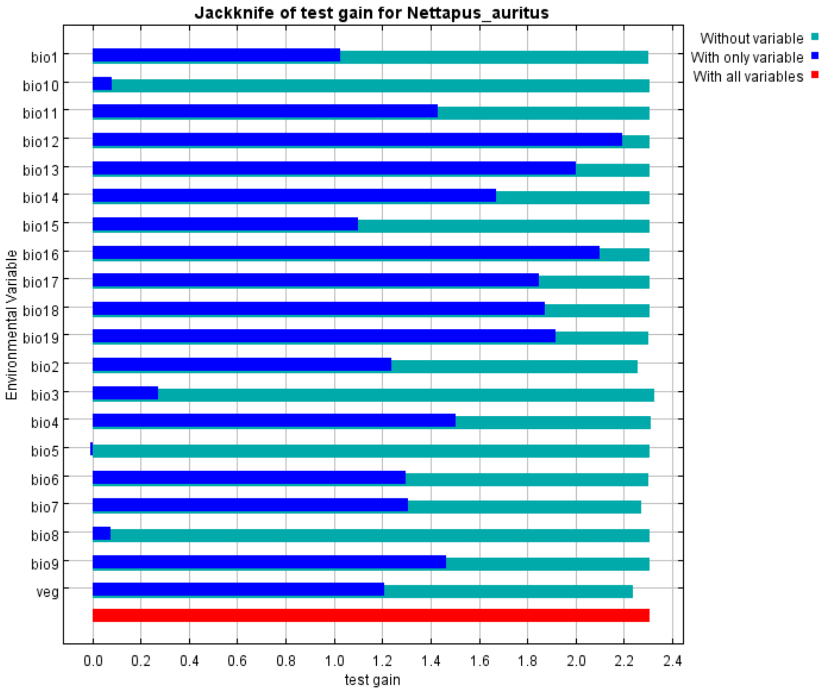

Figure 39: Jackknife of test gain for African Pygmy Goose

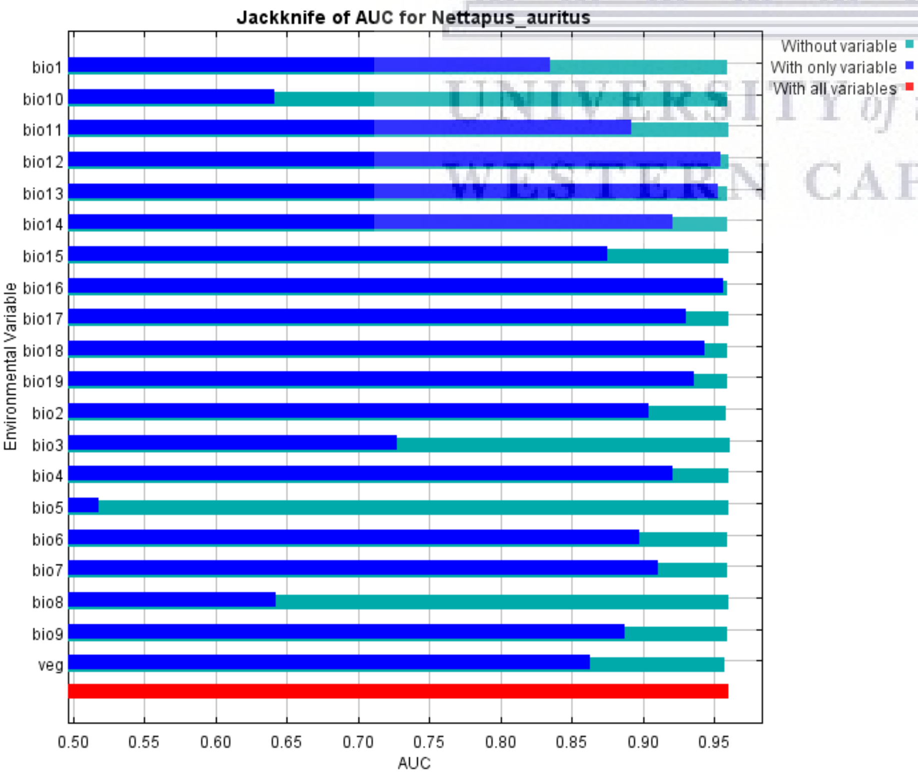

Figure 40: Jackknife of AUC for the African Pygmy Goose

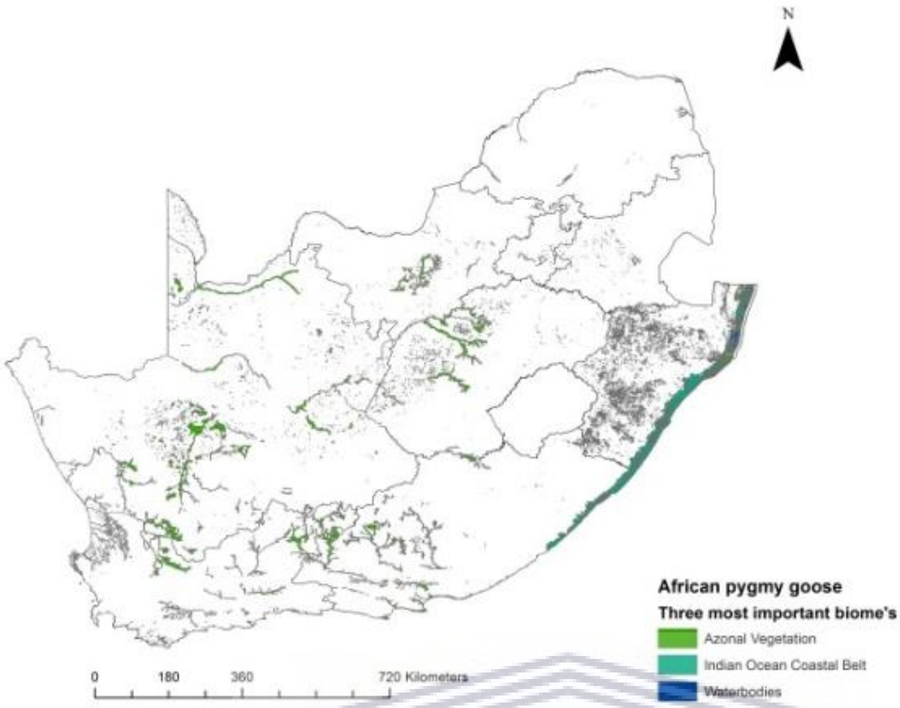

Figure 41: The three most important biomes for the African Pygmy Goose according to MaxEnt

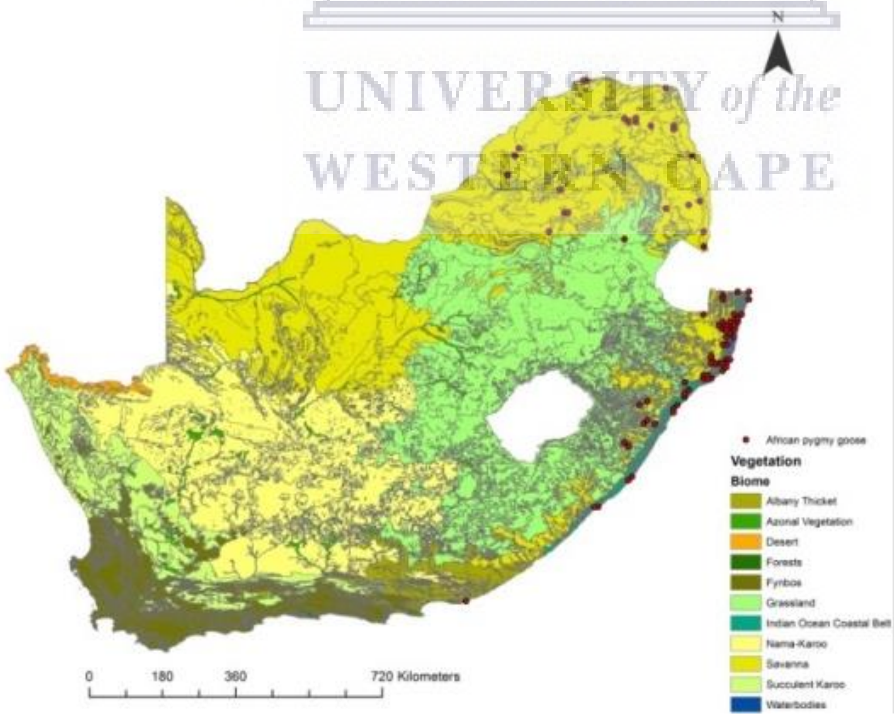

Figure 42: African Pygmy Goose point distributions across the 11 vegetation biomes

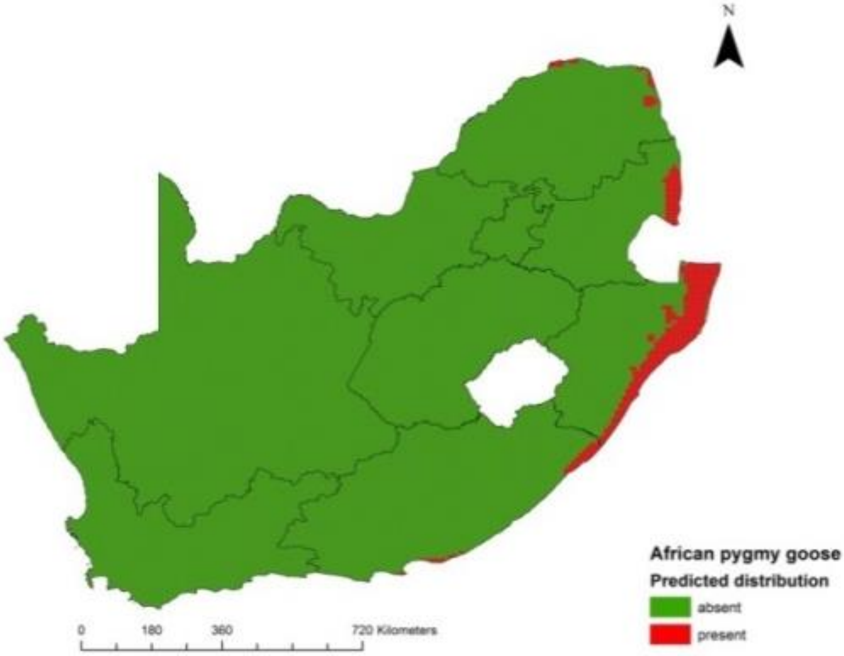

Figure 43: Predicted areas of presence according to MaxEnt for the African Pygmy Goose

Black Stork

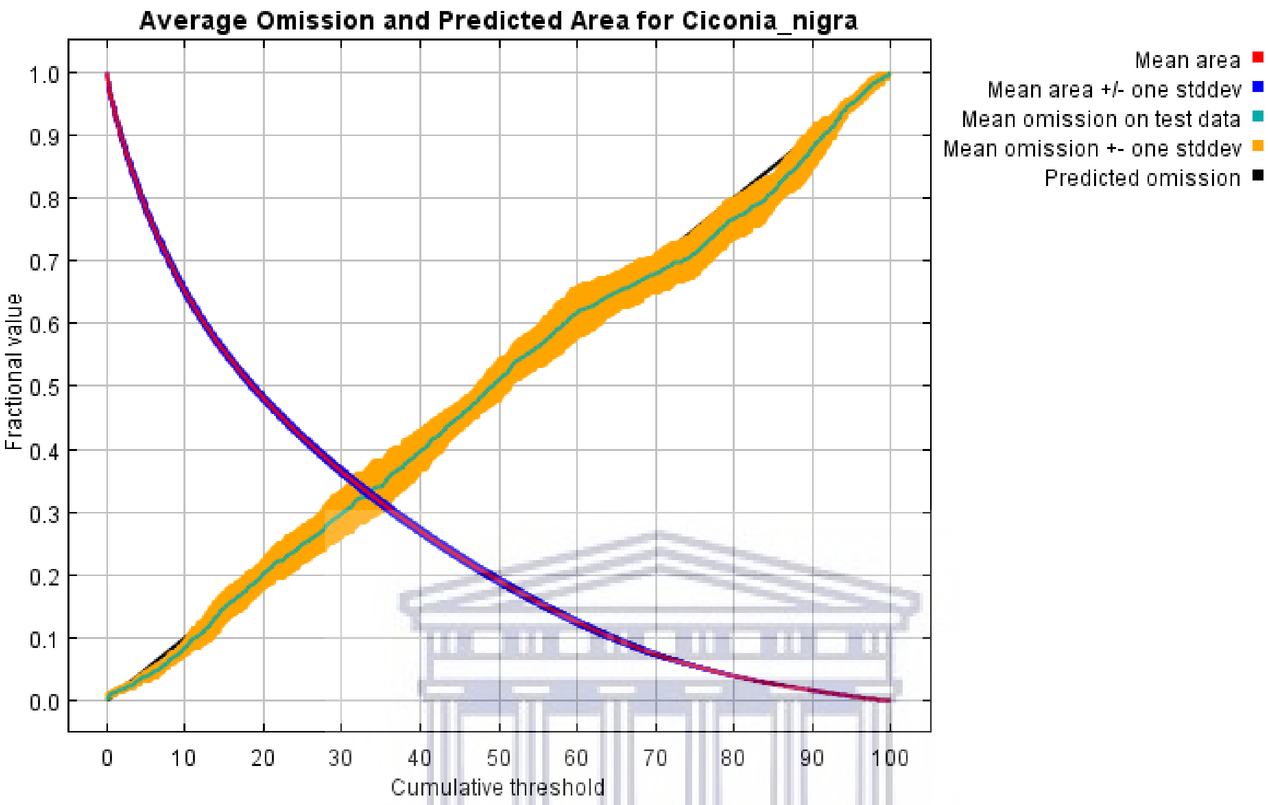

Figure 44: Average Omission and Predicted area for the Black Stork

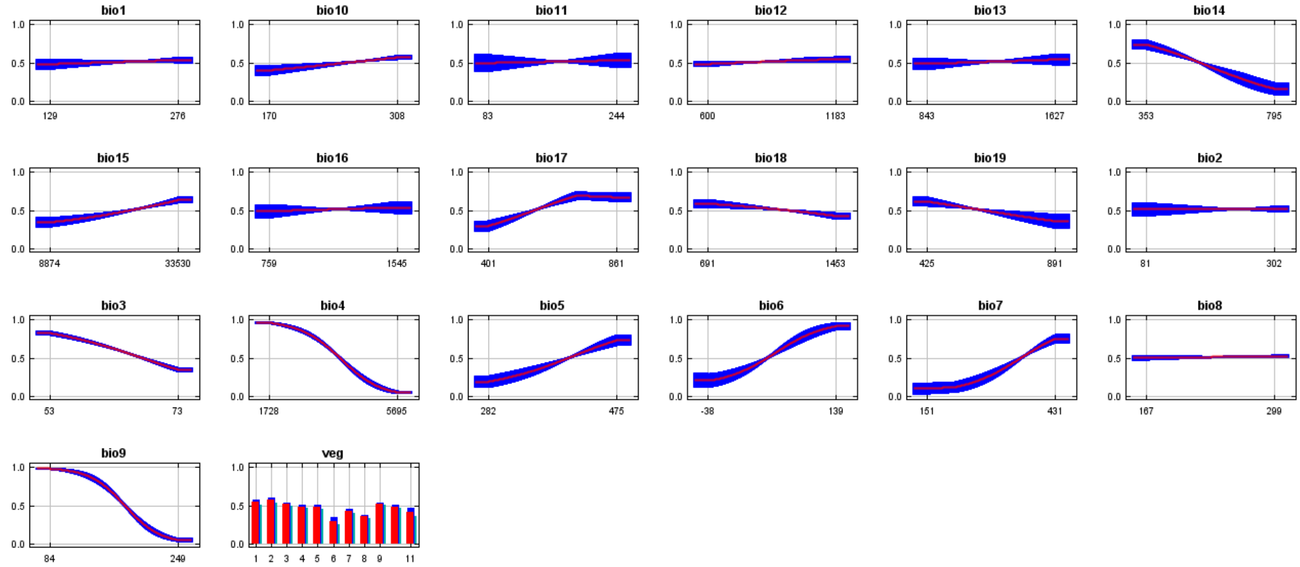

Figure 45: Marginal response curves for the Black Stork

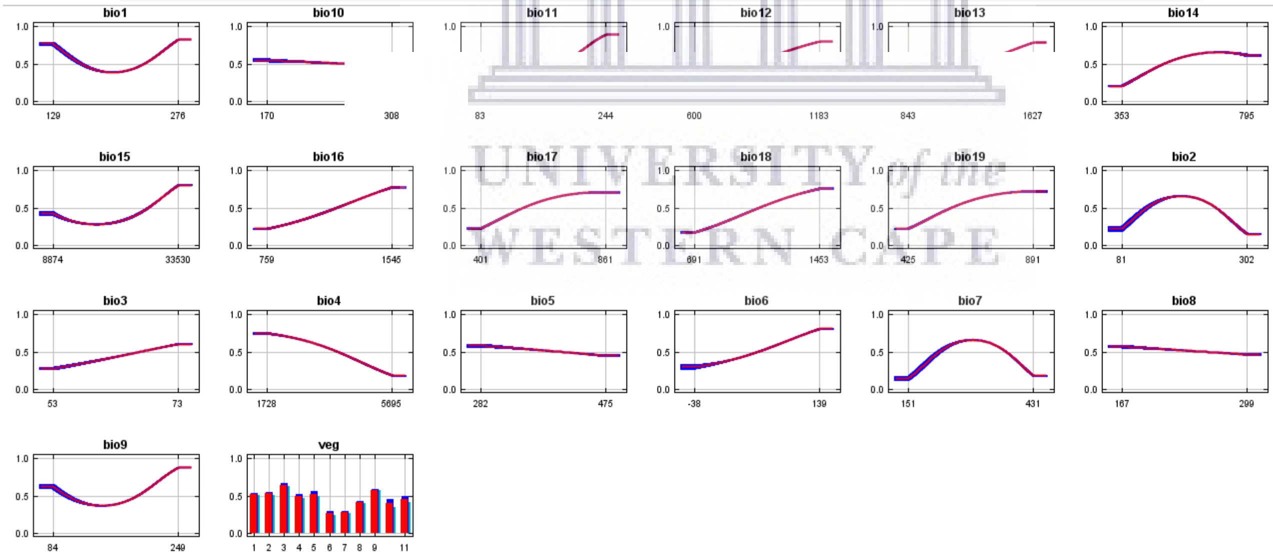

Figure 46: Alternative response curves for the Black Stork

Table 26: Analysis of variable contribution for the Black Stork

Variable	Percent contribution	Permutation importance
bio13	15.4	0.8
bio16	13.7	0.9
bio3	13.5	1.7
veg	12.5	4.6
bio4	8	36.4
bio15	6.8	3.5
bio14	4.5	4.2
bio9	4.3	11
bio12	4.2	0.1
bio17	3.1	8.2
bio18	2.7	1.1
bio19	2.6	1
bio6	2.1	17.1
bio11	1.9	0.7
bio5	1.8	4.2
bio7	1	3.3
bio8	0.6	0.1
bio10	0.5	0.7
bio1	0.5	0.2
bio2	0.2	0.1

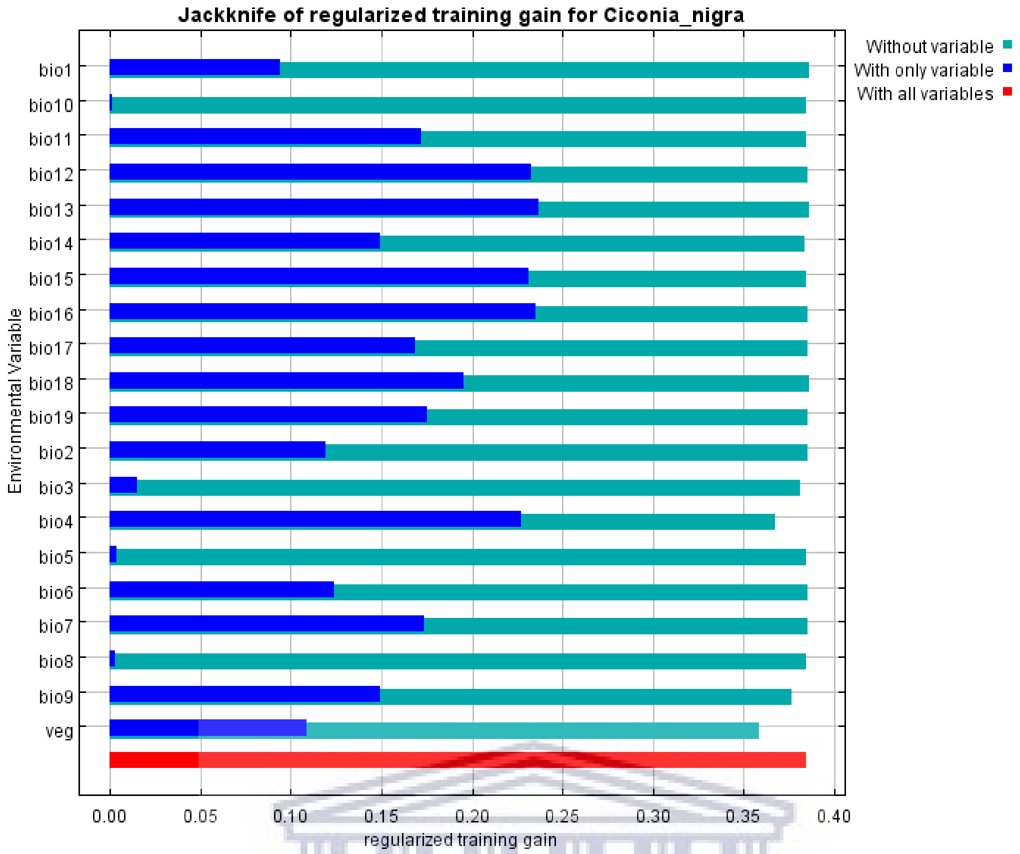

Figure 47: Jackknife of regularized training gain for the Black Stork

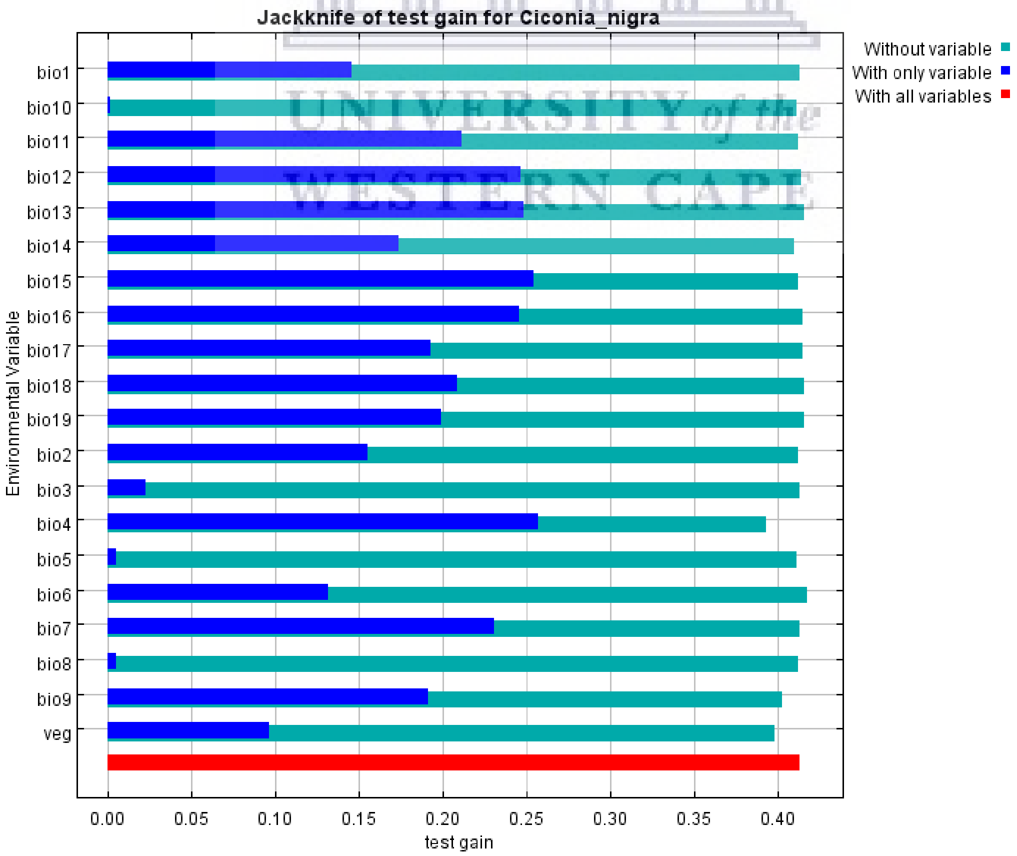

Figure 48: Jackknife of test gain for the Black Stork

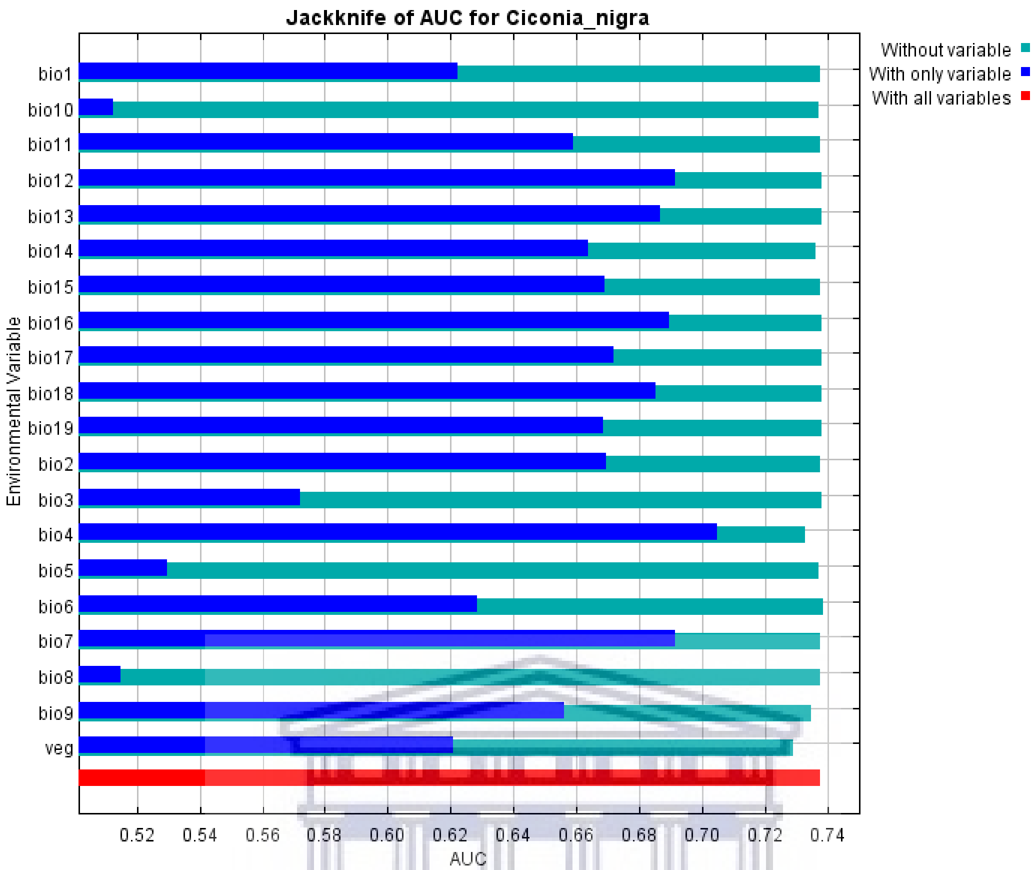

Figure 49: Jackknife of AUC for the Black Stork

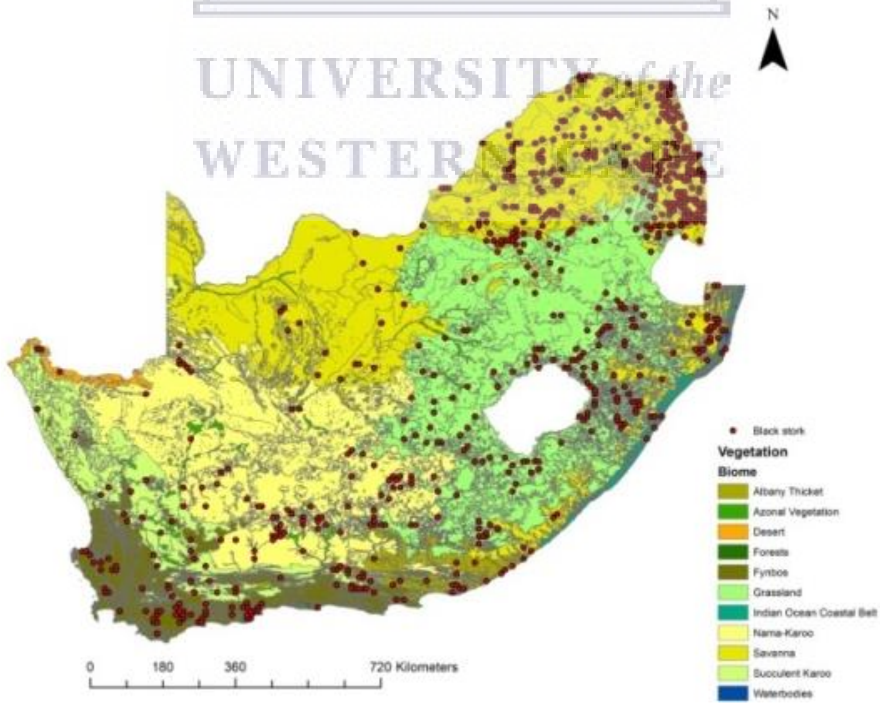

Figure 50: Black Stork point distributions across the 11 vegetation biomes

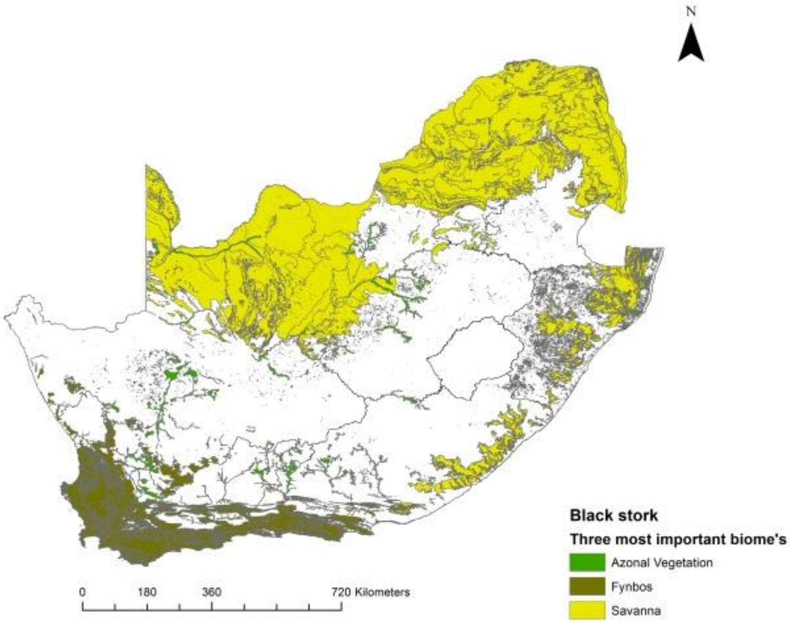

Figure 51: The three most important biomes for the Black Stork according to MaxEnt

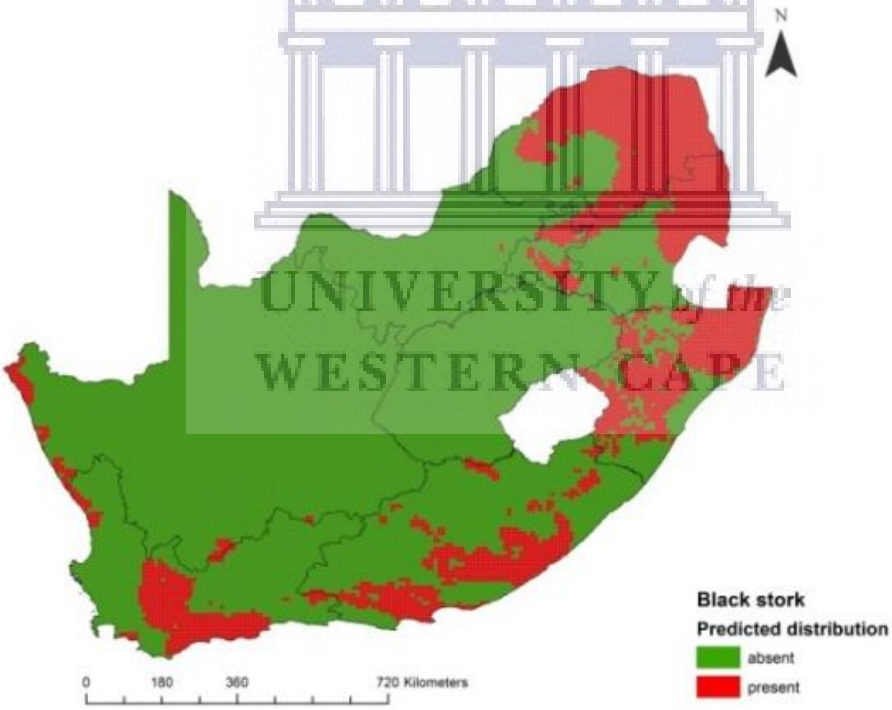

Figure 52: Predicted areas of presence according to MaxEnt for the Black Stork

Grey Crowned Crane

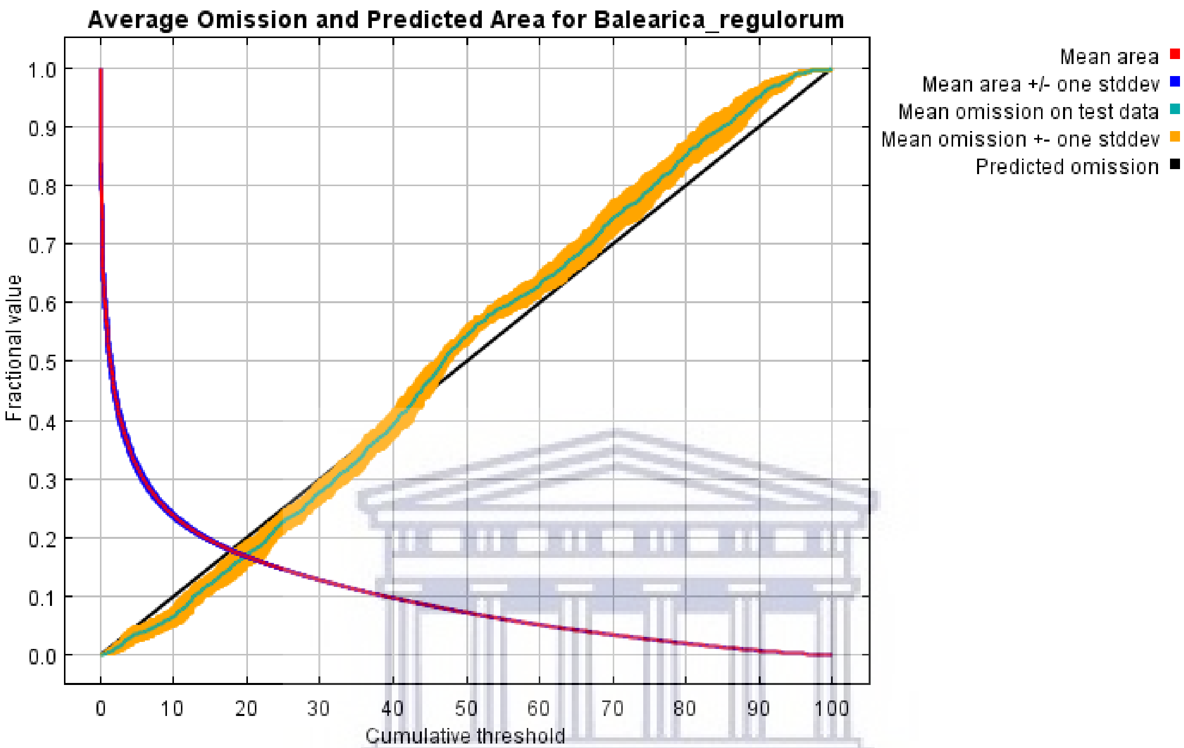

Figure 53: Average Omission and Predicted area for the Grey Crowned Crane

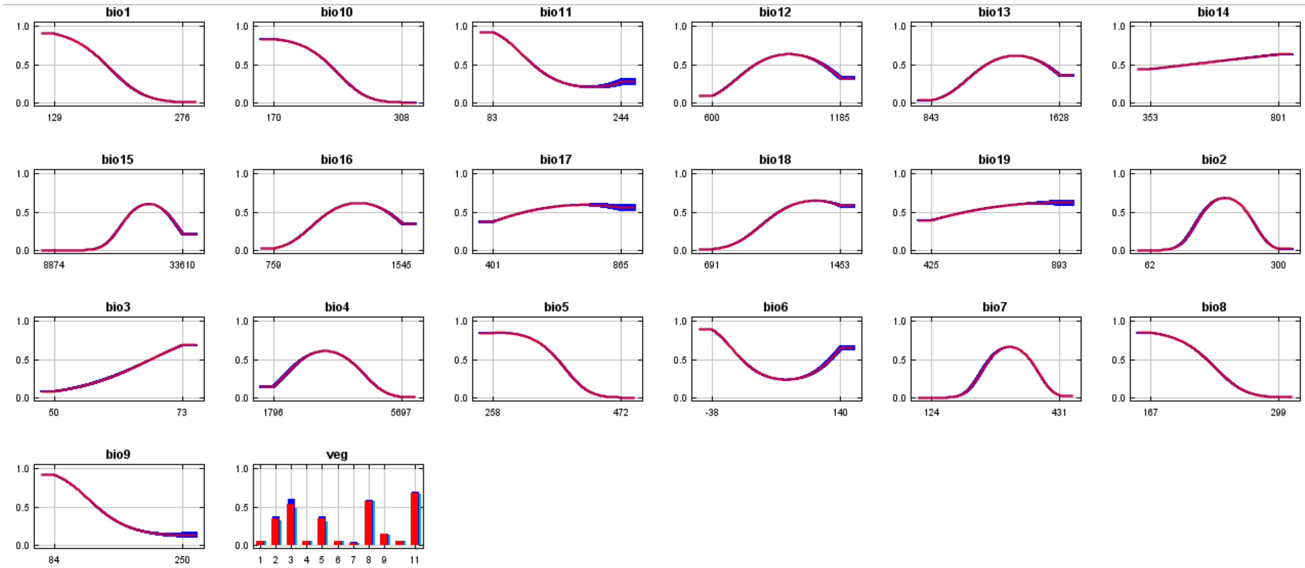

Figure 54:Alternative response curves for the Grey Crowned Crane

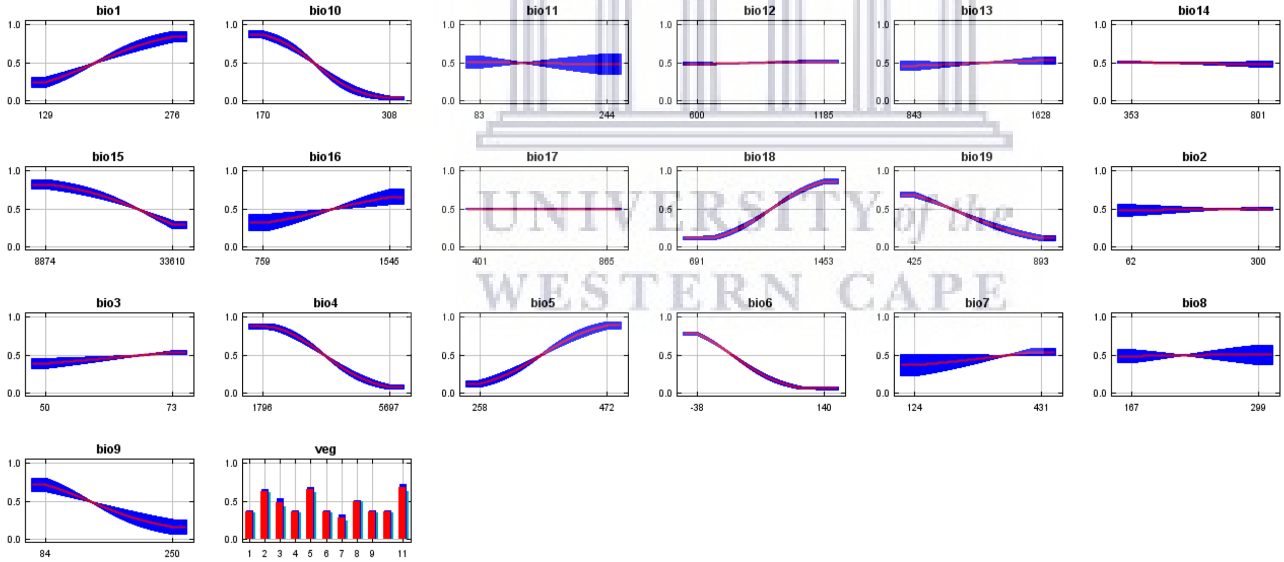

Figure 55: Marginal response curves for the Grey Crowned Crane

Table 27: Analysis of variable contribution for the Black Stork

Variable	Percent contribution	Permutation importance
veg	38.5	2.9
bio4	13.8	23
bio10	9.3	27.2
bio5	7.3	1.9
bio1	5.7	1.4
bio8	5.6	0.3
bio15	3.1	4
bio3	3	0.1
bio9	2.6	4.9
bio7	2.5	0.1
bio18	2.1	14
bio11	1.8	0.5
bio16	1.2	2.8
bio6	0.9	12.2
bio12	0.7	0
bio13	0.6	0.3
bio2	0.5	0
bio19	0.4	4.3
bio17	0.2	0
bio14	0.1	0.1

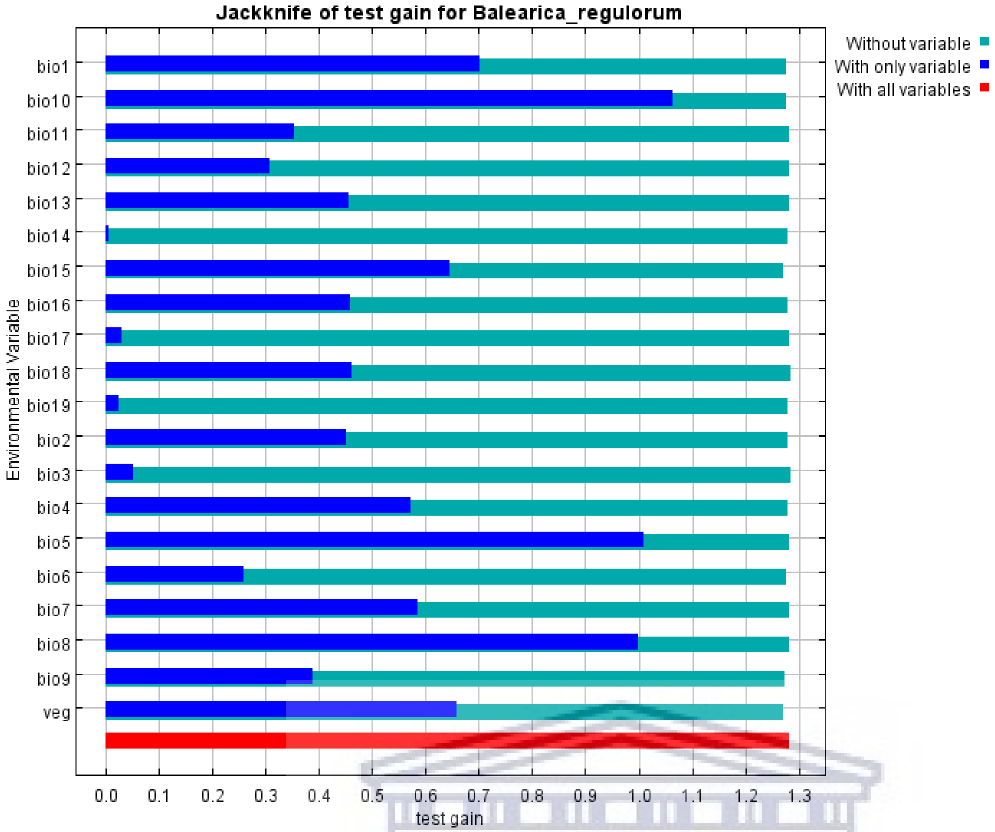

Figure 56: Jackknife of test gain for Grey Crowned Crane

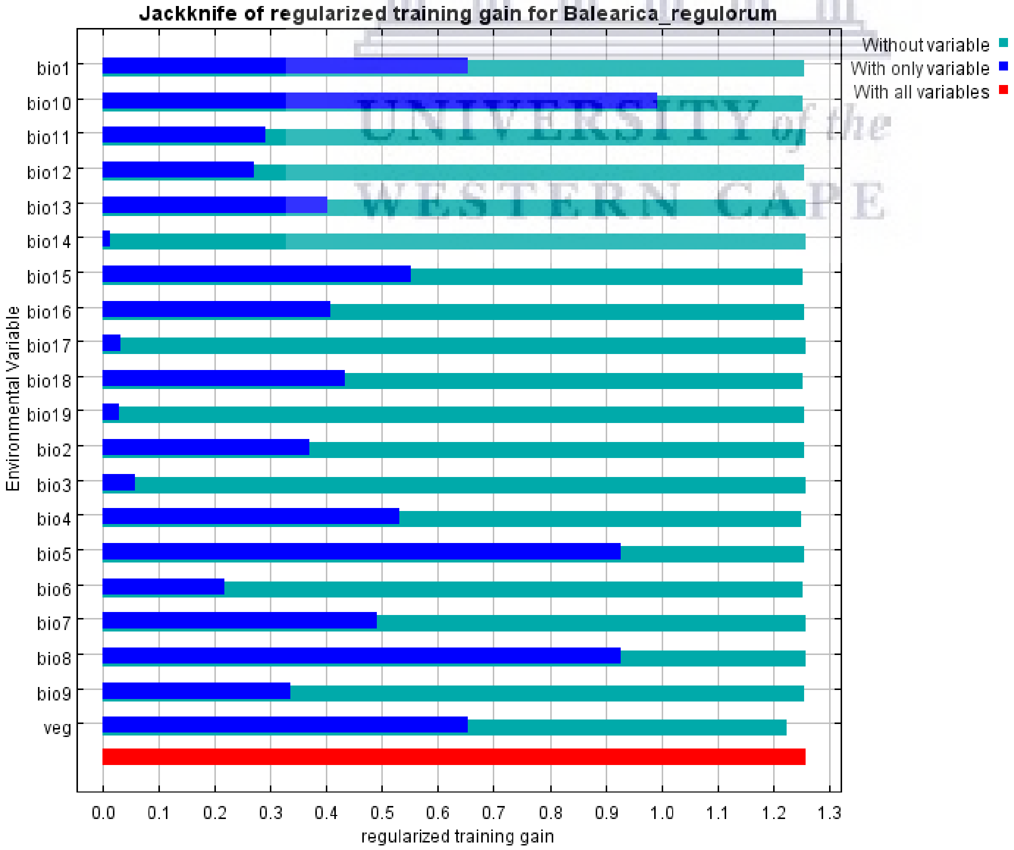

Figure 57: Jackknife of regularized training gain for the Grey Crowned Crane

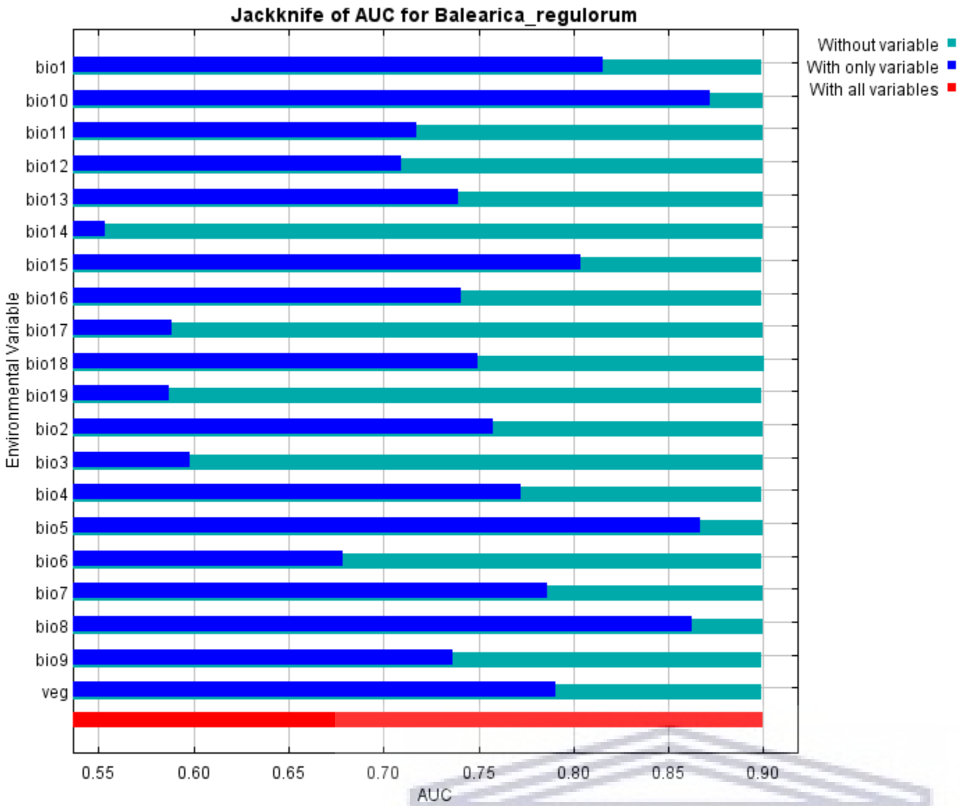

Figure 58: Jackknife of AUC for the Grey Crowned Crane

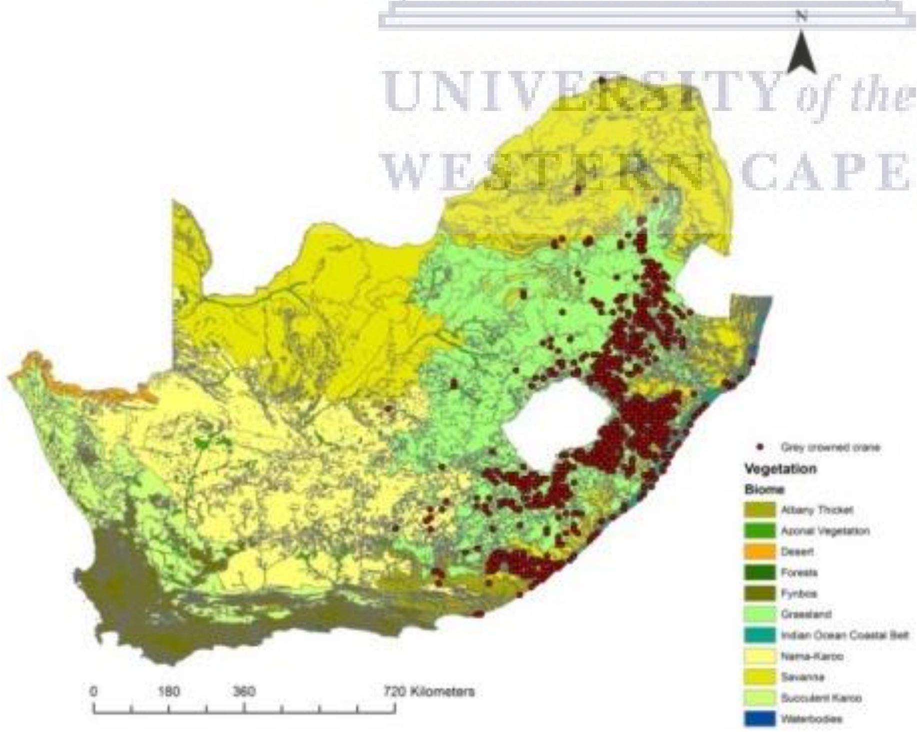

Figure 59: Grey Crowned Crane point distributions across the 11 vegetation

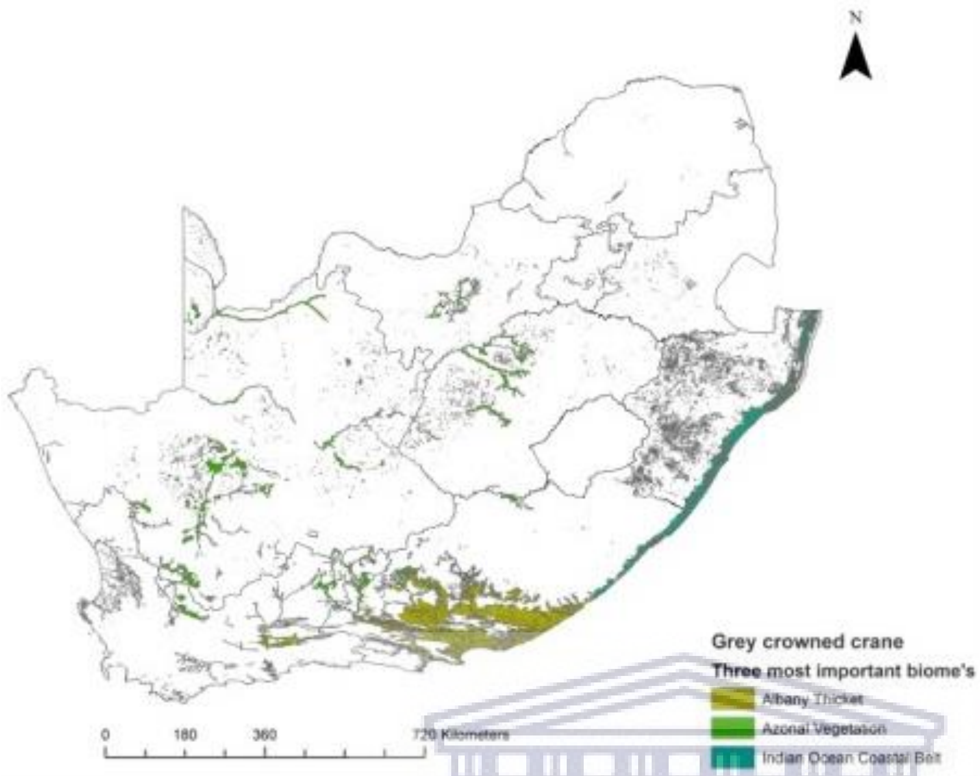

Figure 60: The three most important biomes for the Grey Crowned Crane according to MaxEnt

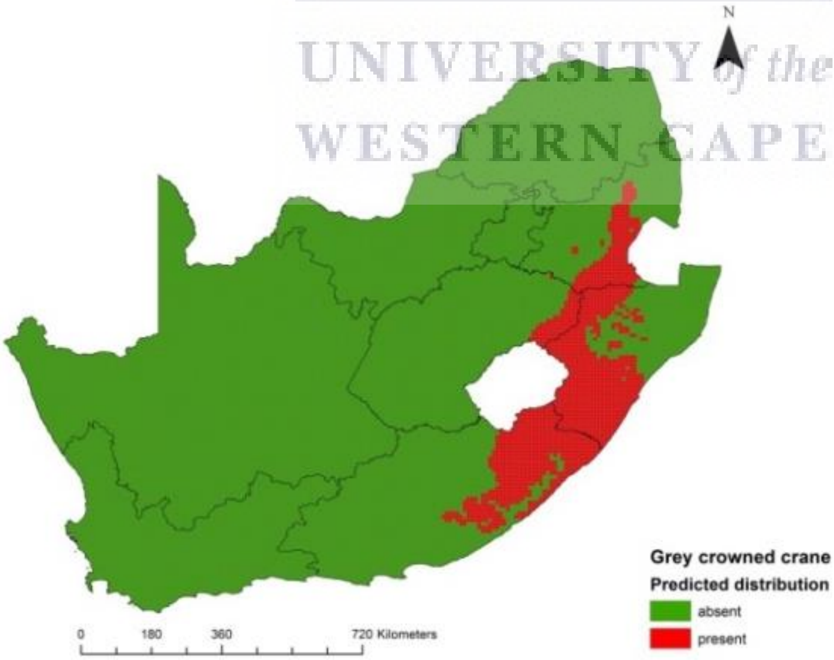

Figure 61: Predicted areas of presence according to MaxEnt for the Grey Crowned Crane

GreatWhitePelican

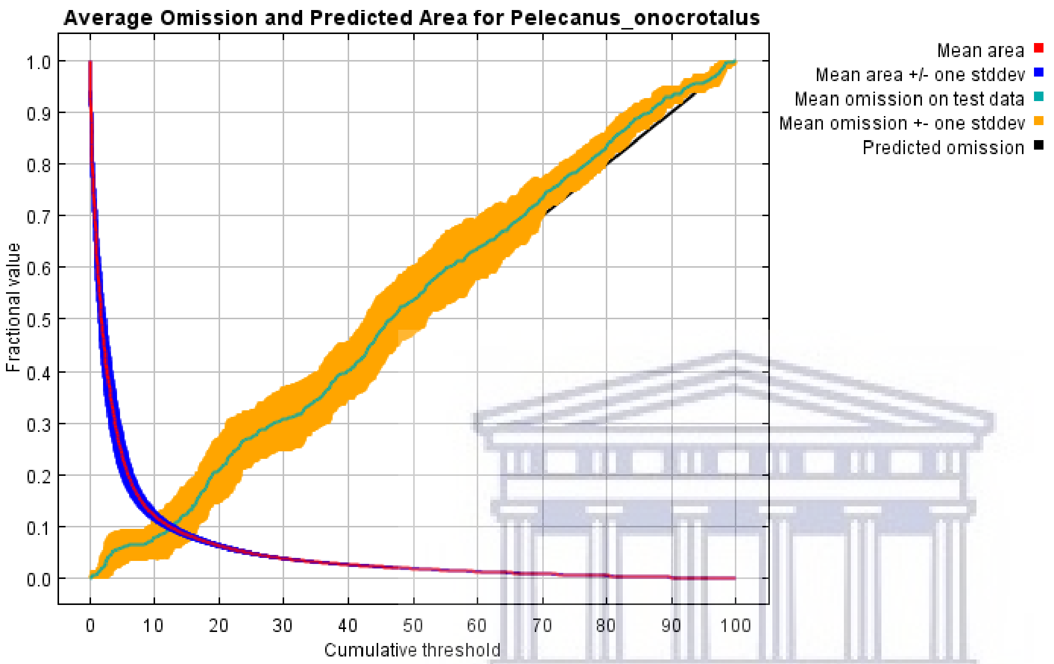

Figure 62: Average Omission and Predicted area for the Great White Pelican

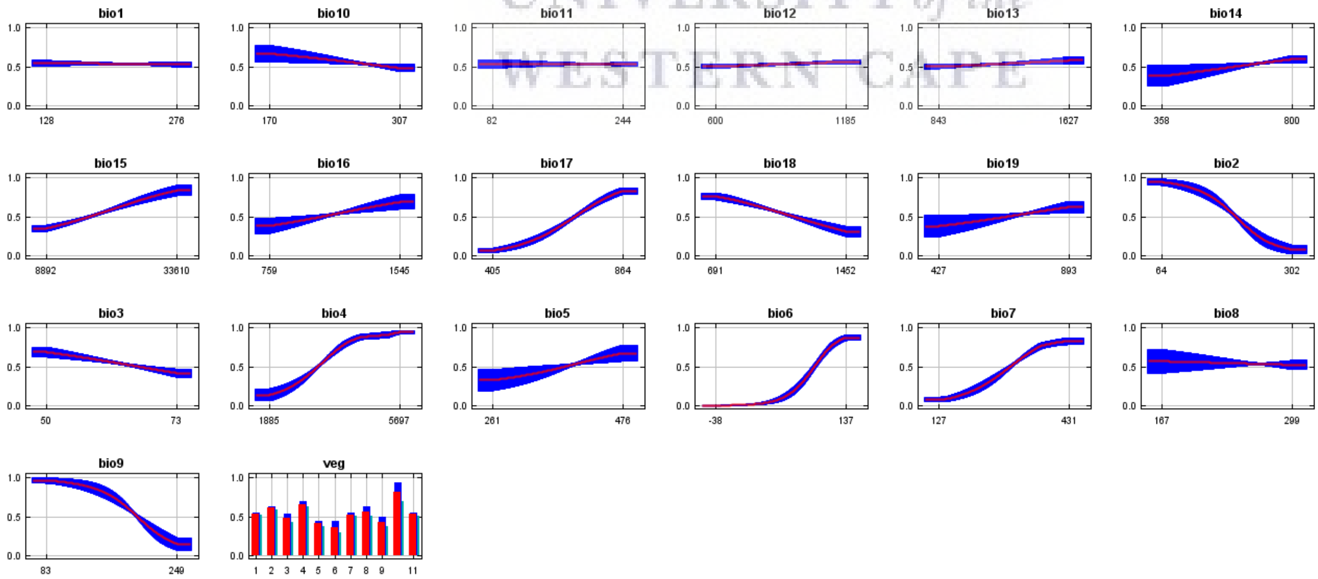

Figure 63: Marginal response curves for the Great White Pelican

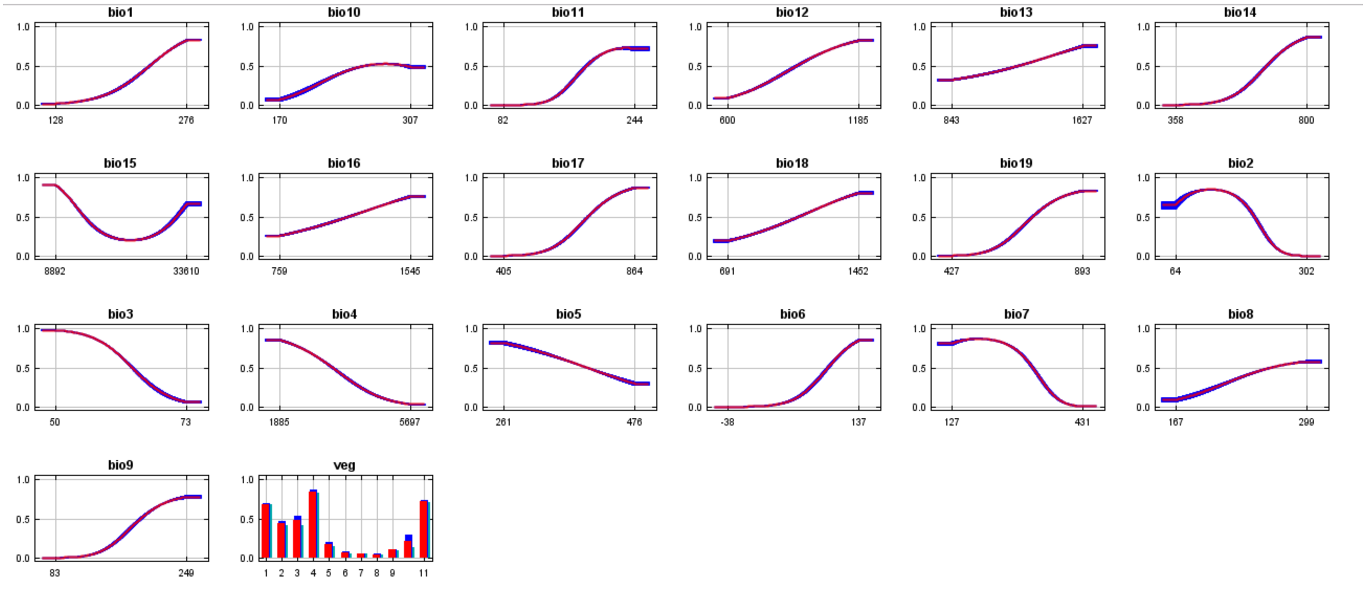

Figure 64: Alternative response curves for the Great White Pelican

Table 28: Analysis of variable contribution for the Great White Pelican

Variable	Percent contribution	Permutation importance
bio6	36.8	60.5
veg	20.7	1.5
bio14	8.6	0.7
bio17	7.2	10.6
bio19	6	0.4
bio4	5.2	5.9
bio12	1.8	0.1
bio2	1.7	10.9
bio7	1.6	0.6
bio3	1.5	0.2
bio10	1.5	0.3
bio15	1.4	1.4
bio8	1.3	0.2
bio18	1.1	0.9
bio11	0.8	0
bio9	0.6	3.5
bio1	0.6	0.1
bio5	0.6	0.4
bio13	0.5	0.2
bio16	0.3	1.7

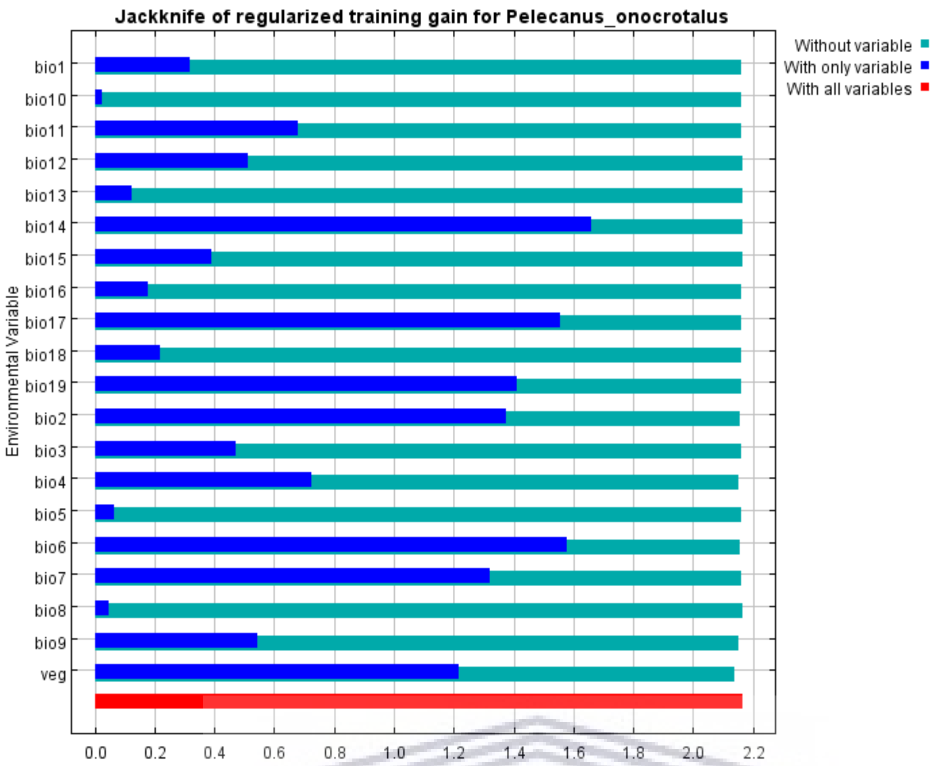

Figure 65: Jackknife of regularized training gain for the Great White Pelican

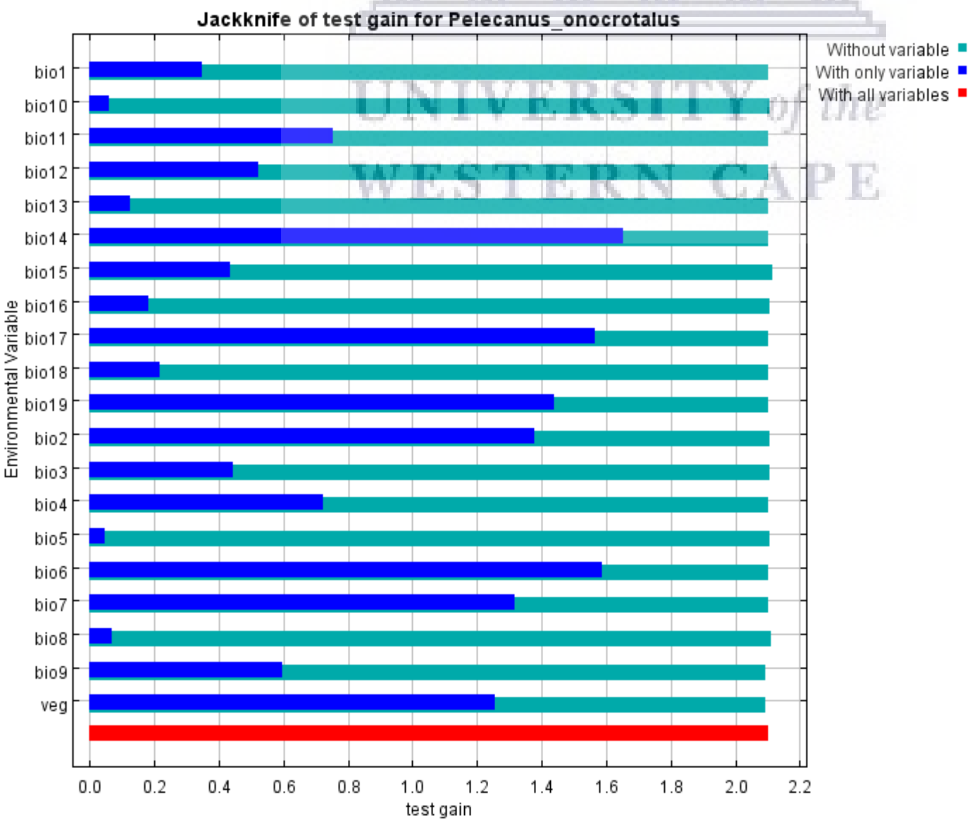

Figure 66: Jackknife of test gain for the Great White Pelican

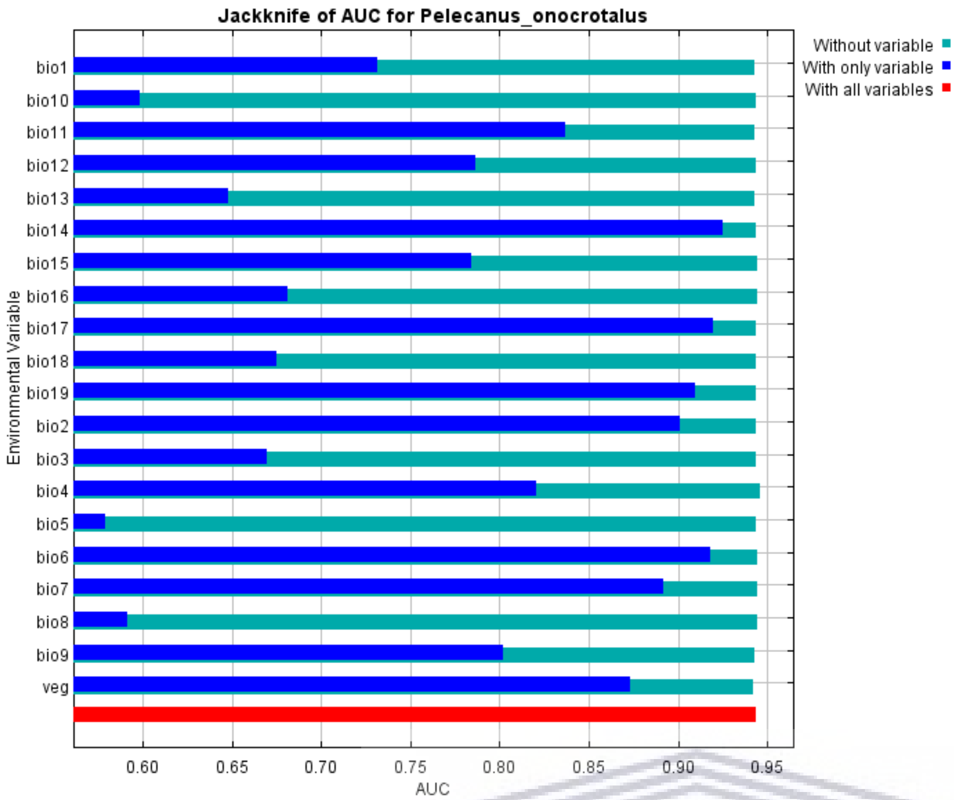

Figure 67: Jackknife of AUC for the Great White Pelican

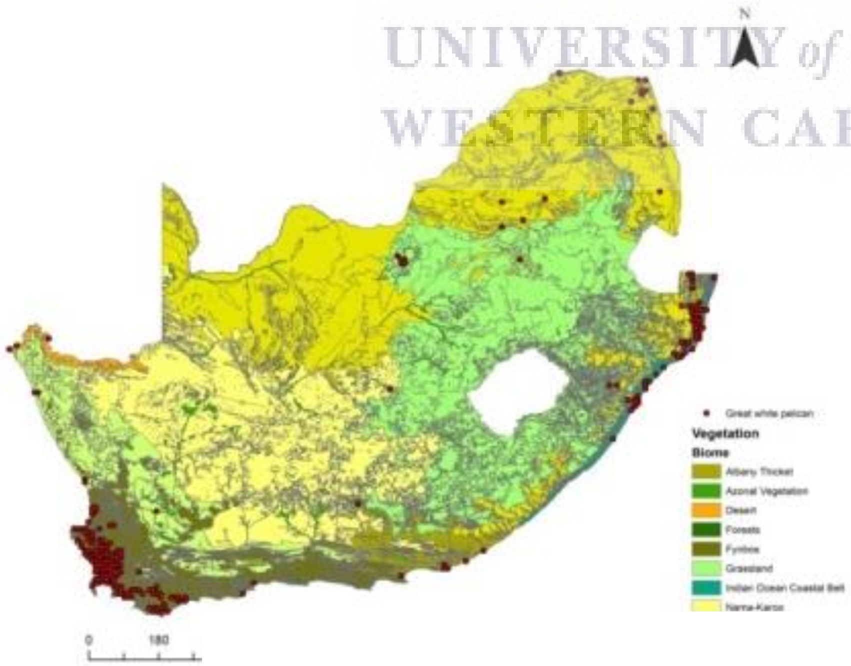

Figure 68: Great White Pelican point distributions across the 11 vegetation

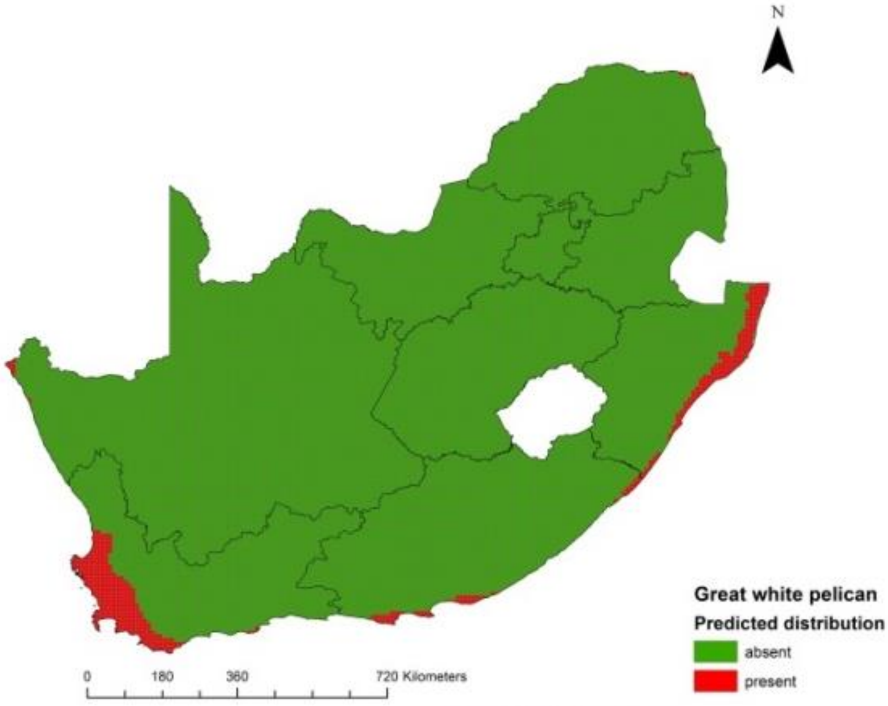

Figure 69: The three most important biomes for the Great White Pelican according to MaxEnt

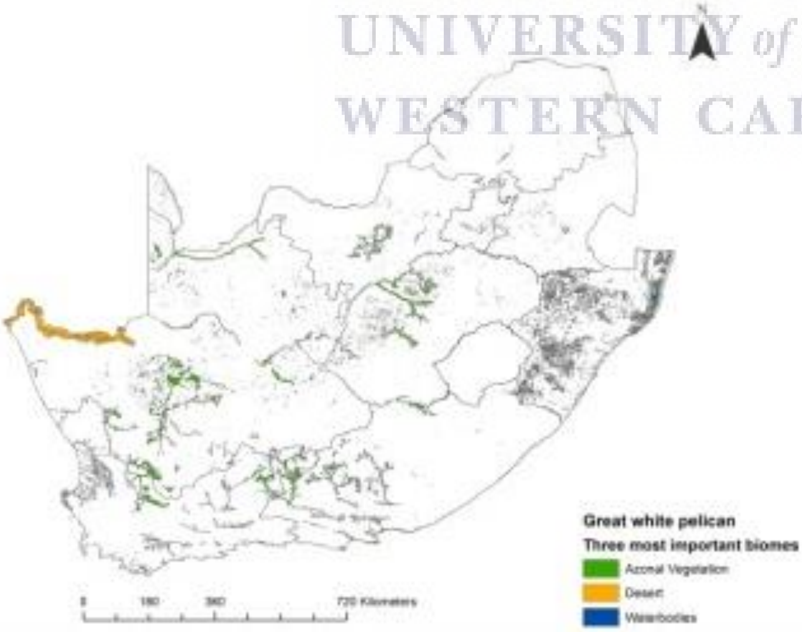

Figure 70: Predicted areas of presence according to MaxEnt for the Great White Pelican

Lesser Jacana

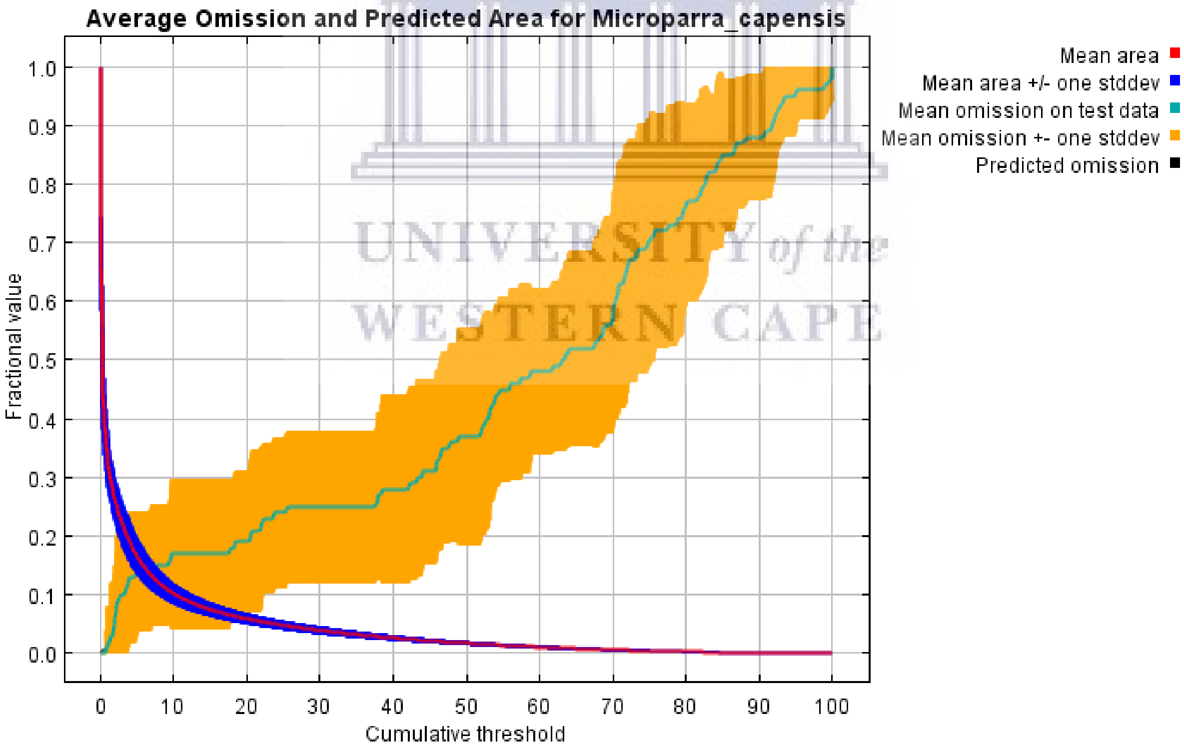

Figure 71: Average Omission and Predicted area for the Lesser Jacana

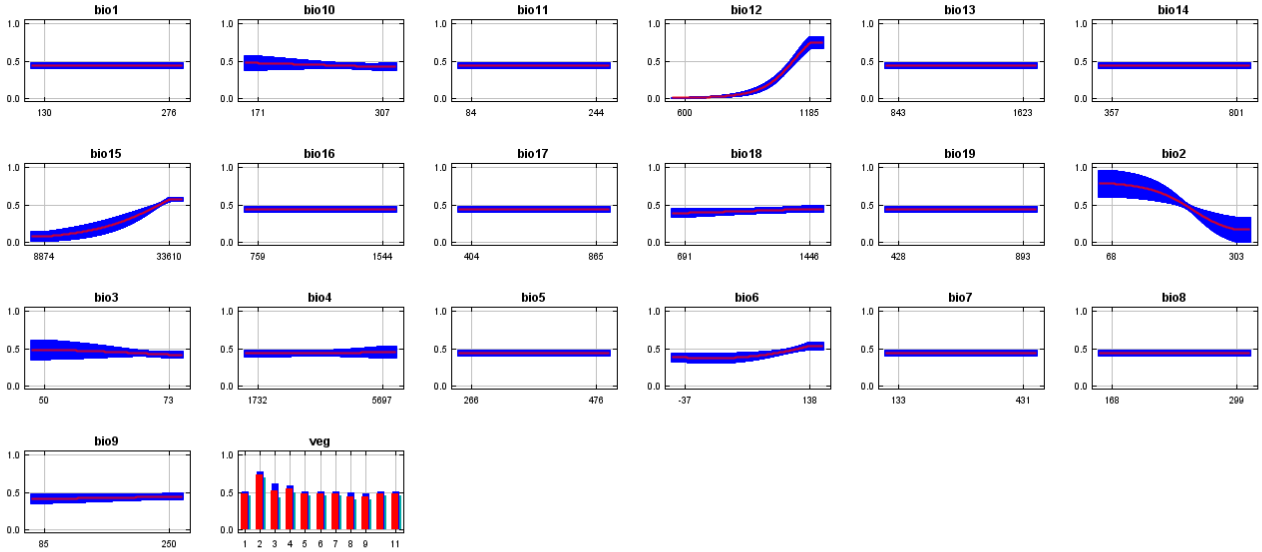

Figure 72: Marginal response curves for the Great White Pelican

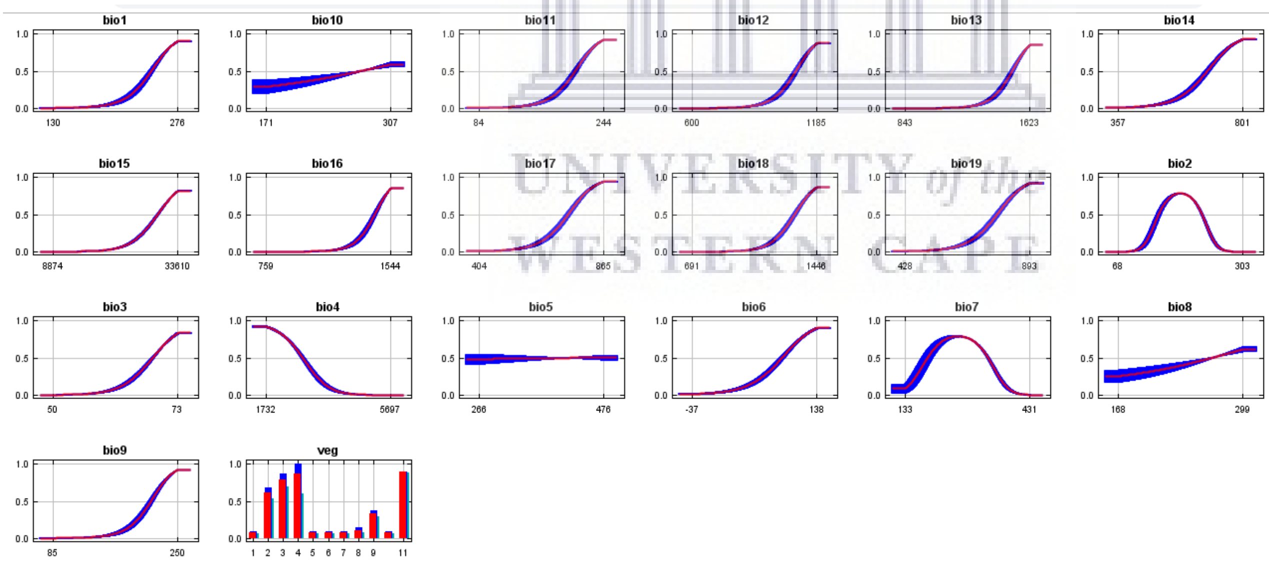

Figure 73: Alternative response curves for the Lesser Jacana

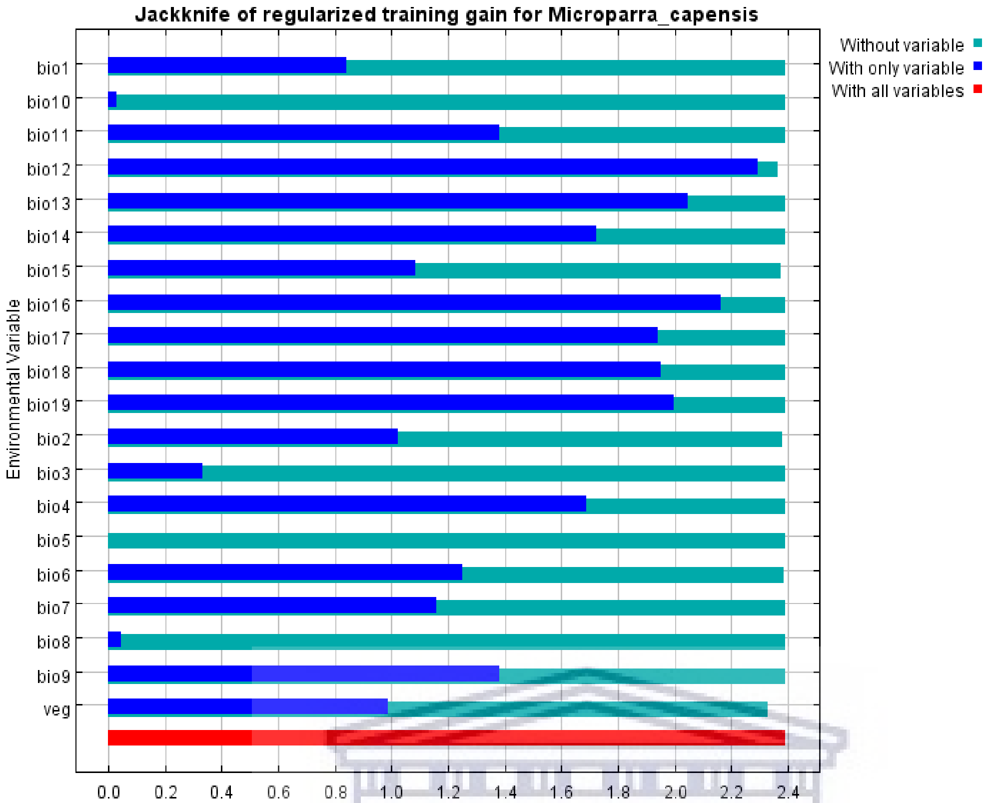

Figure 74: Jackknife of regularized training gain for the Lesser Jacana

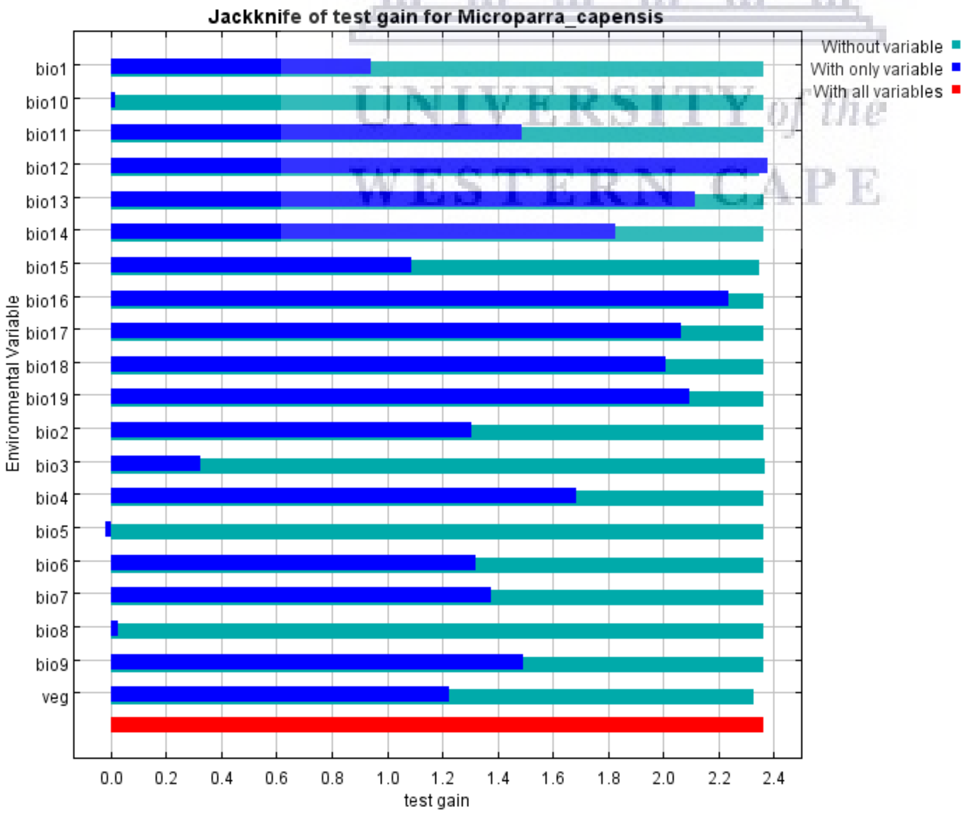

Figure 75: Jackknife of test gain for the Lesser Jacana

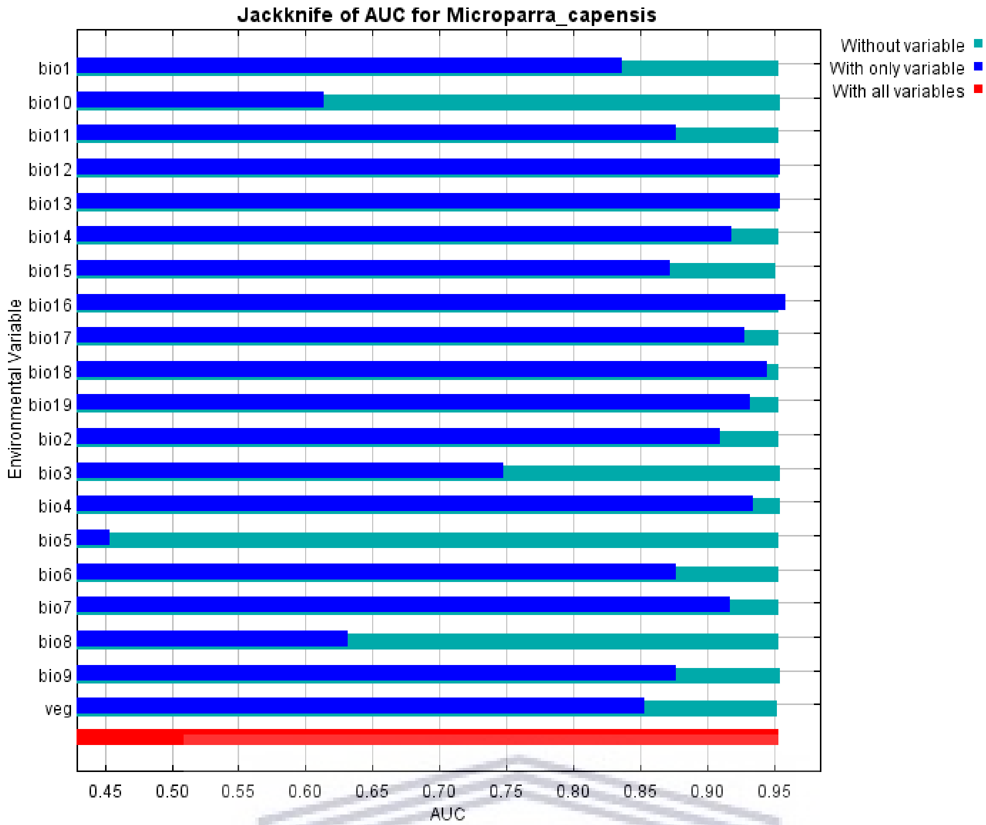

Figure 76: Jackknife of AUC for the Lesser Jacana

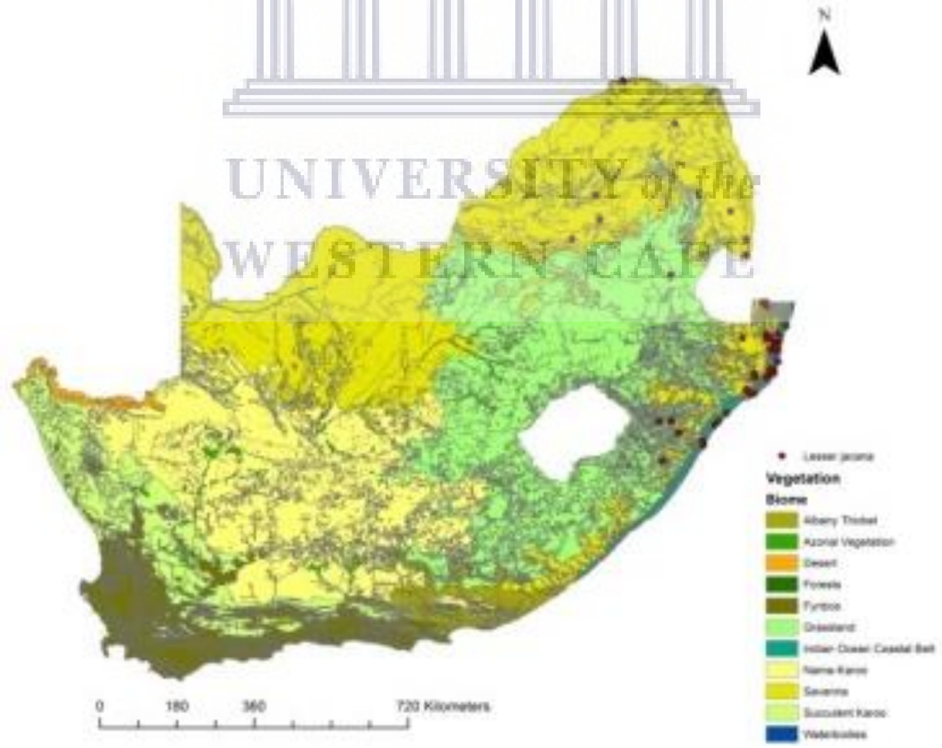

Figure 77: Lesser Jacana point distributions across the 11 vegetation biomes

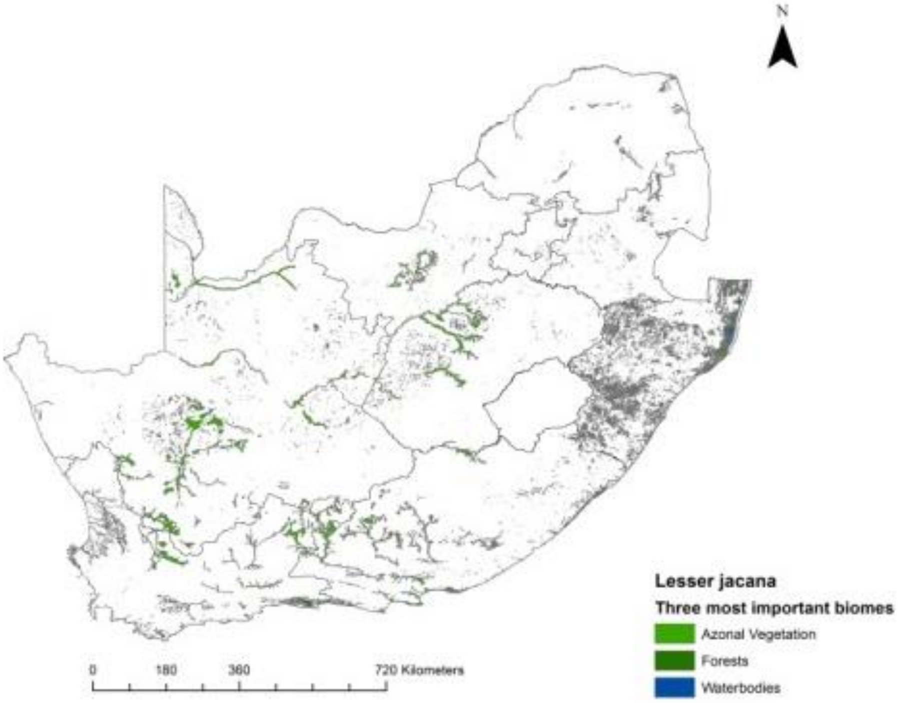

Figure 78: The three most important biomes for the Lesser Jacana according to MaxEnt

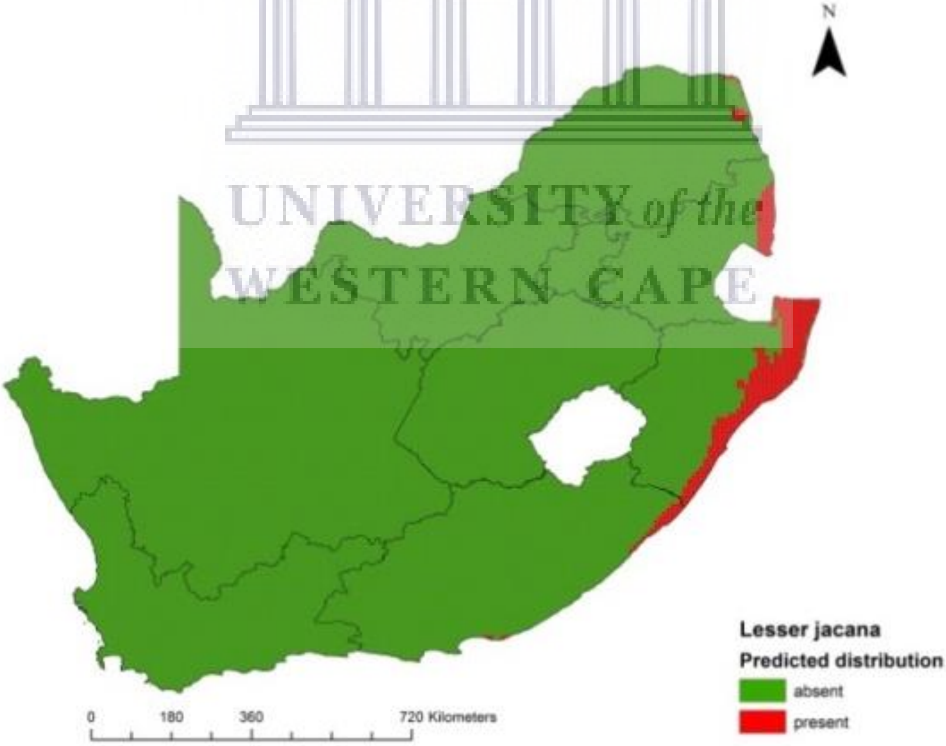

Figure 79: Predicted areas of presence according to MaxEnt for the Lesser Jacana

Table 29: Analysis of variable contribution for the Pink Backed Pelican

Variable	Percent contribution	Permutation importance
bio12	58.5	65.9
bio16	9.2	0
bio13	6.2	0
bio19	5.7	0
bio17	4.5	0
veg	3.4	1
bio6	3.2	0
bio18	2.7	0.4
bio4	1.6	0.4
bio15	1.6	20.9
bio14	1.3	0
bio9	0.7	0
bio11	0.6	0
bio2	0.4	10.6
bio7	0.2	0
bio1	0.1	0
bio10	0.1	0.5
bio3	0	0.2
bio8	0	0
bio5	0	0

Pink Backed Pelican

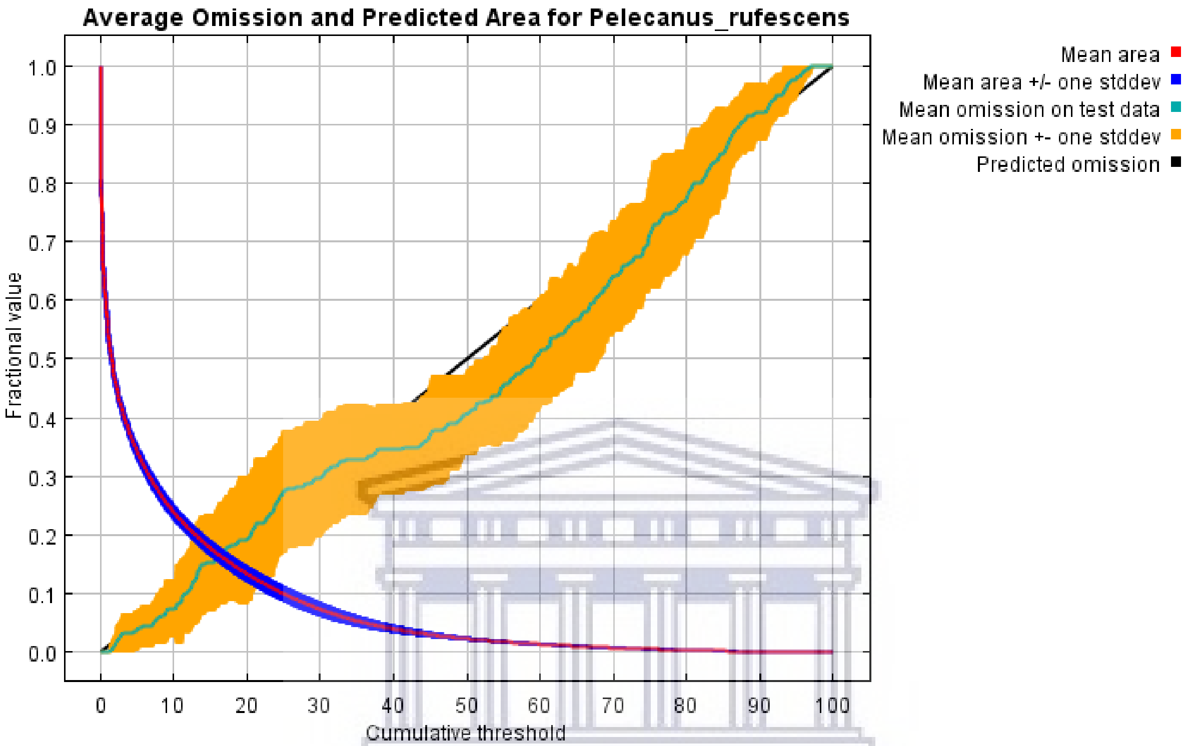

Figure 80: Average Omission and Predicted area for the Pink Backed Pelican

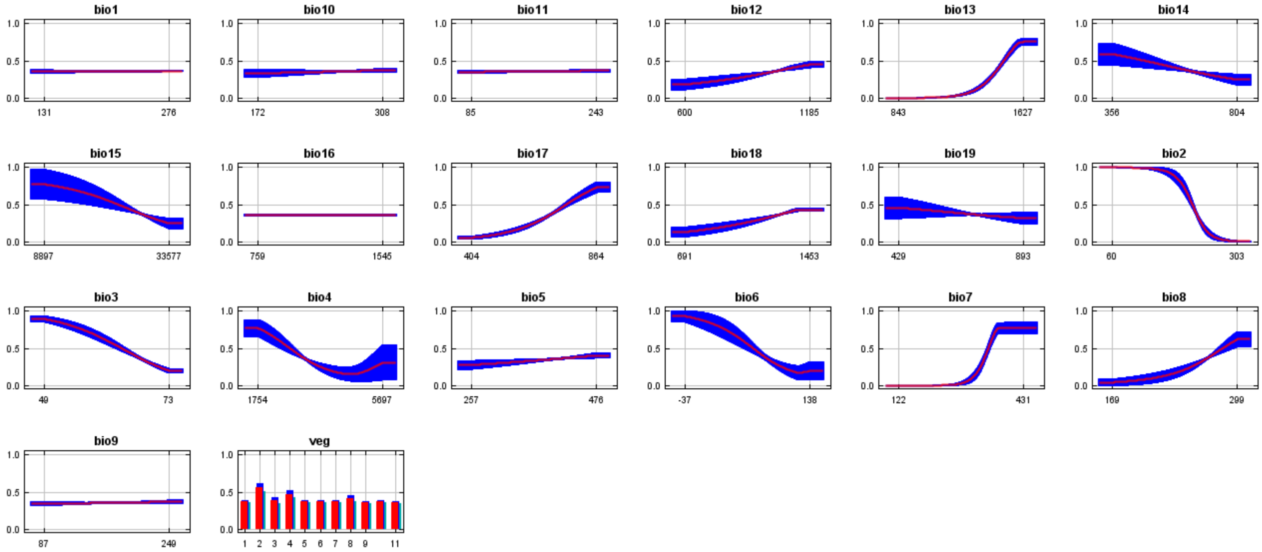

Figure 81: Marginal response curves for the Pink Backed Pelican:

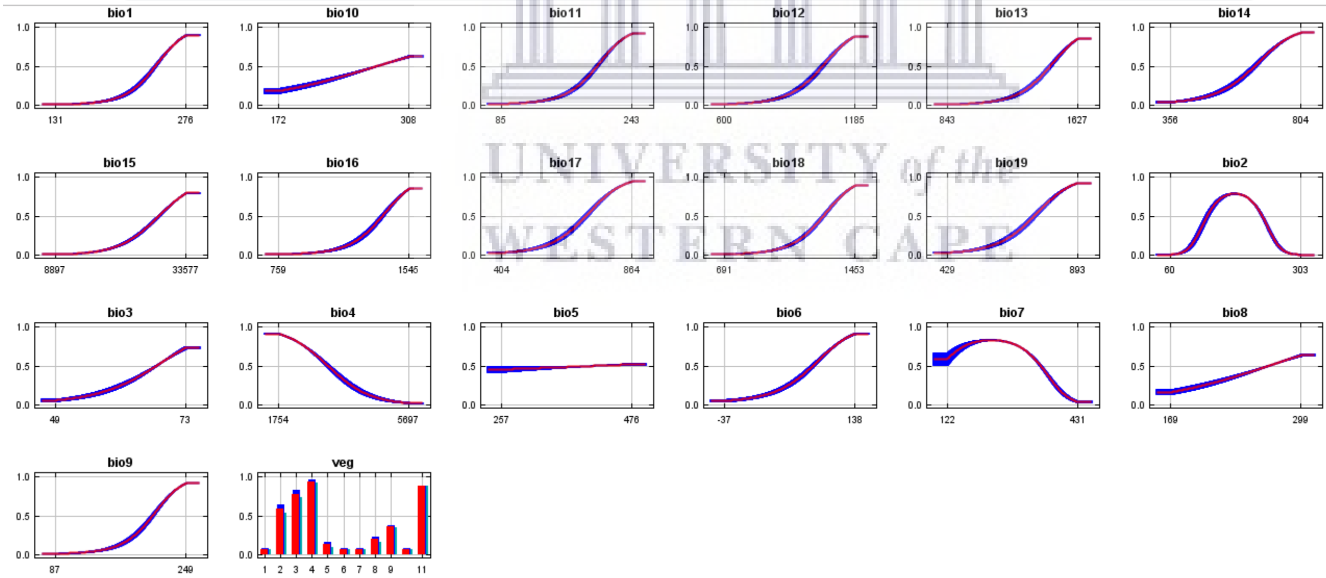

Figure 82: Alternative response curves for the Pink Backed Pelican

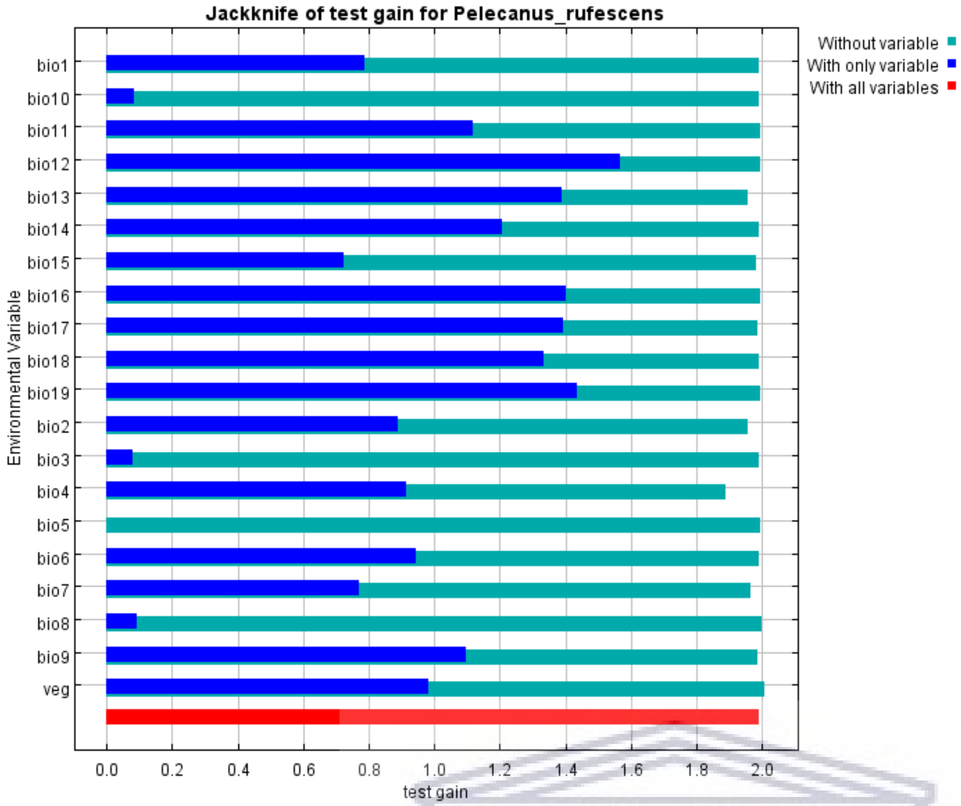

Figure 83: Jackknife of regularized training gain for the Pink Backed Pelican

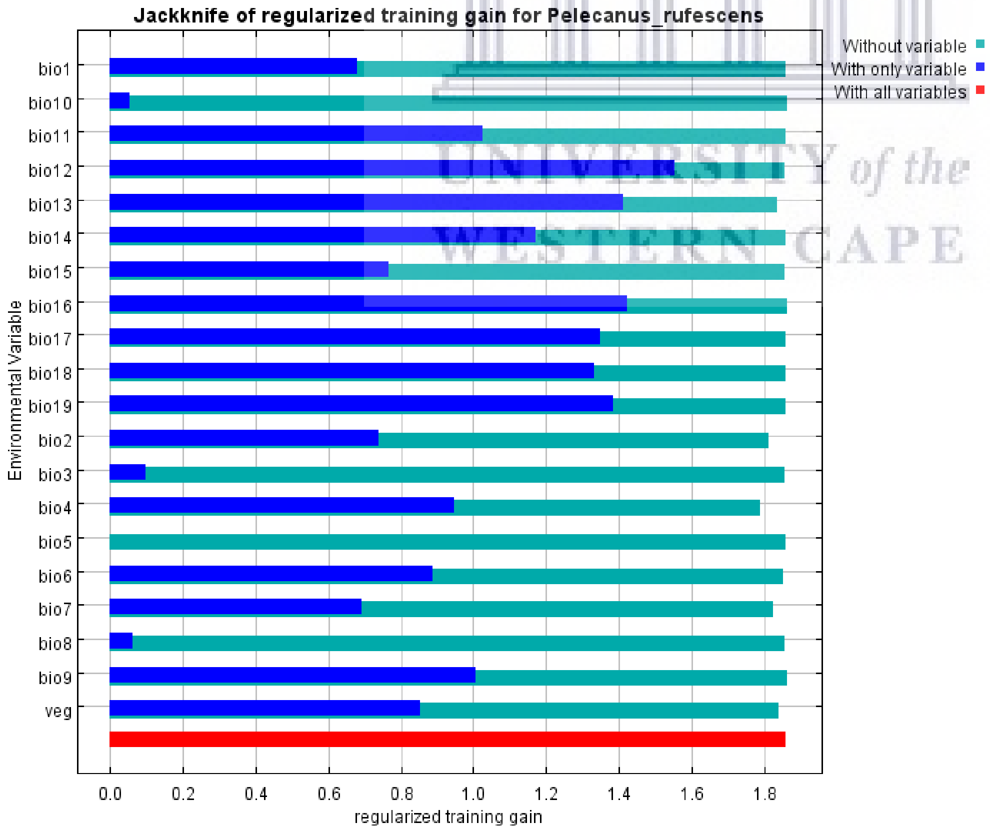

Figure 84: Jackknife of training gain for the Pink Backed Pelican

Table 30: Analysis of variable contribution for the Pink Backed Pelican

Variable	Percent contribution	Permutation importance
bio16	21.2	0
bio19	17.7	0.4
bio12	15.5	0.7
bio13	13.5	49.8
bio17	9.2	8.3
veg	3.5	0.3
bio3	2.9	0.9
bio18	2.5	0.3
bio4	2.4	2
bio14	2	1.4
bio6	1.8	3.2
bio15	1.7	1.6
bio8	1.6	2.9
bio9	0.9	0
bio11	0.8	0
bio5	0.7	0.1
bio7	0.7	6.8
bio2	0.6	21.4
bio10	0.6	0
bio1	0	0

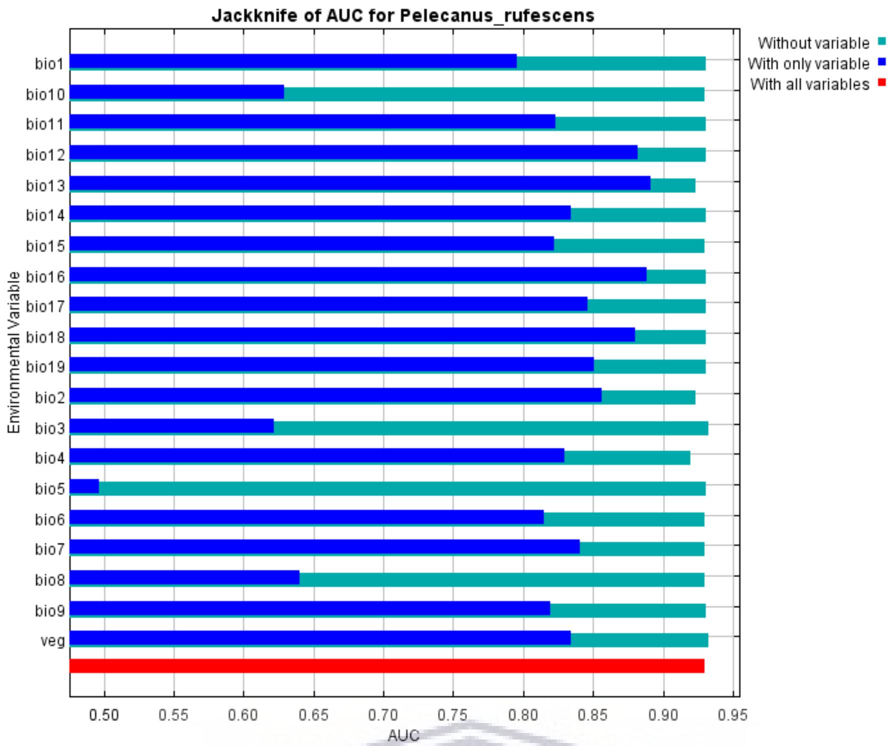

Figure 85: Jackknife of AUC for the Pink Backed Pelican

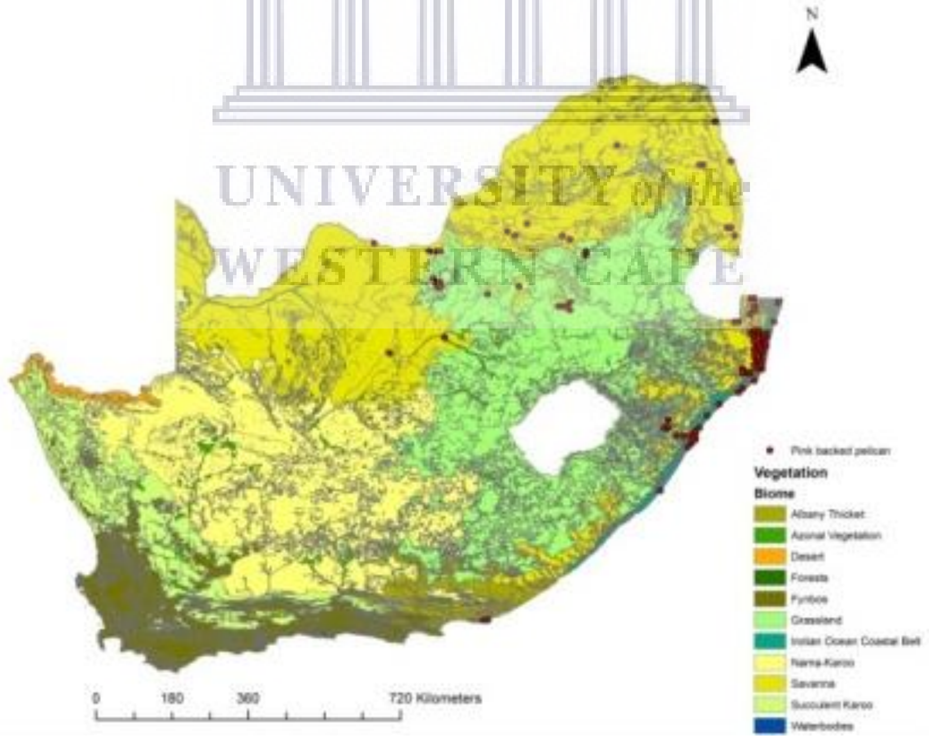

Figure 86: Pink Backed Pelican point distributions across the 11 vegetation biomes

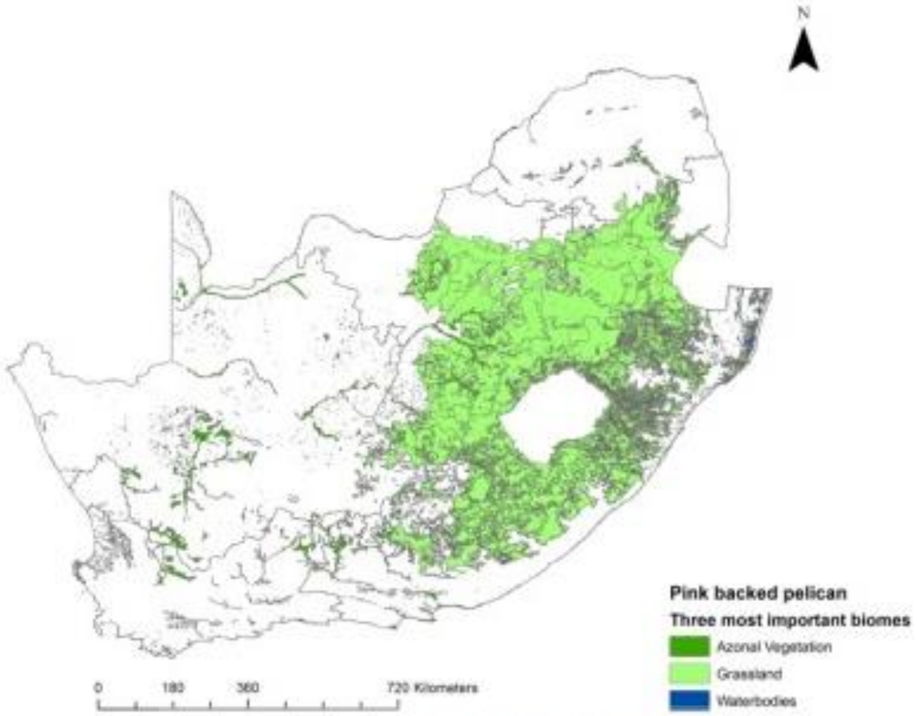

Figure 87: The three most important biomes for the Pink Backed Pelican according to MaxEnt

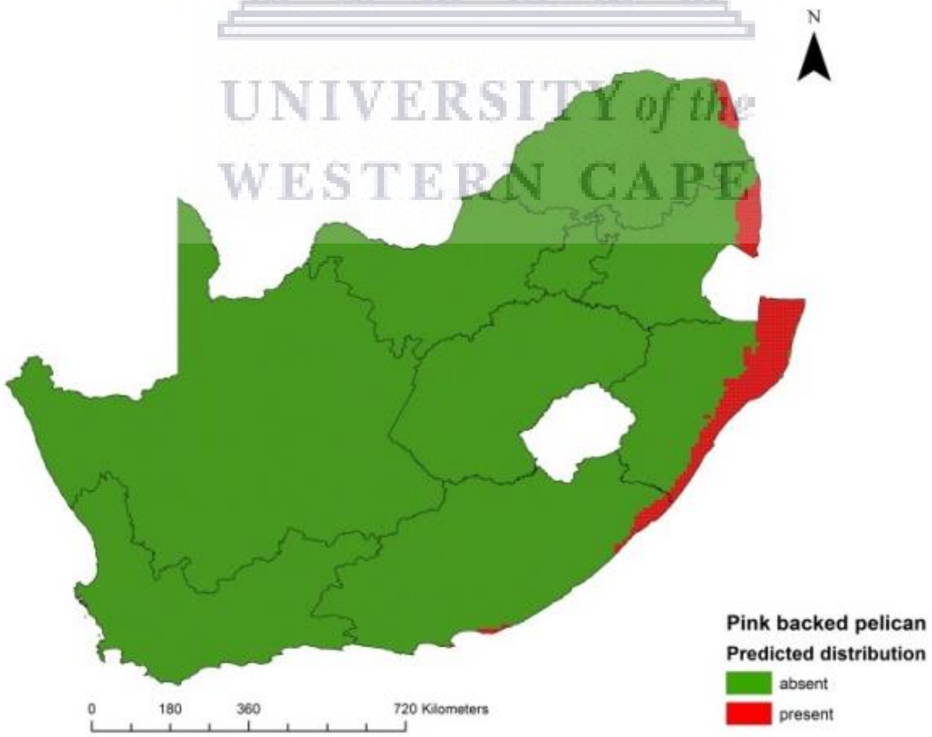

Figure 88: Predicted areas of presence according to MaxEnt for the Pink Backed Pelican

Saddle Billed Stork

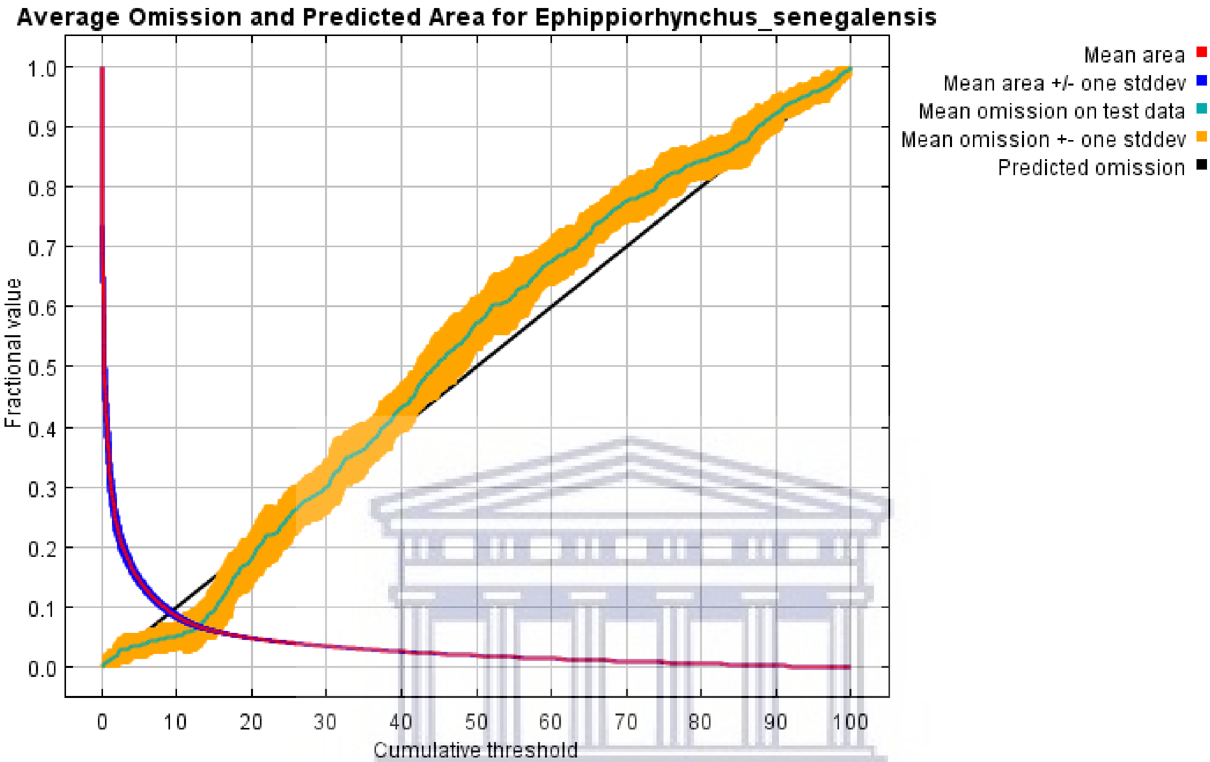

Figure 89: Average Omission and Predicted area for the Saddle Billed Stork

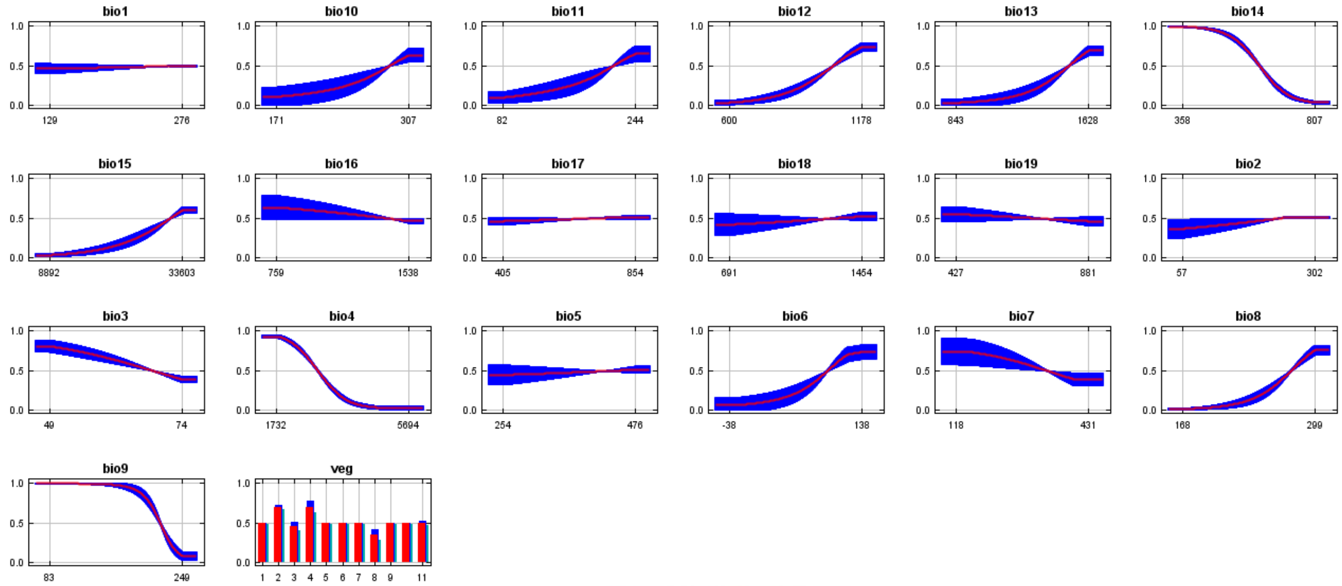

Figure 90: Marginal response curves for the Saddle Billed Stork

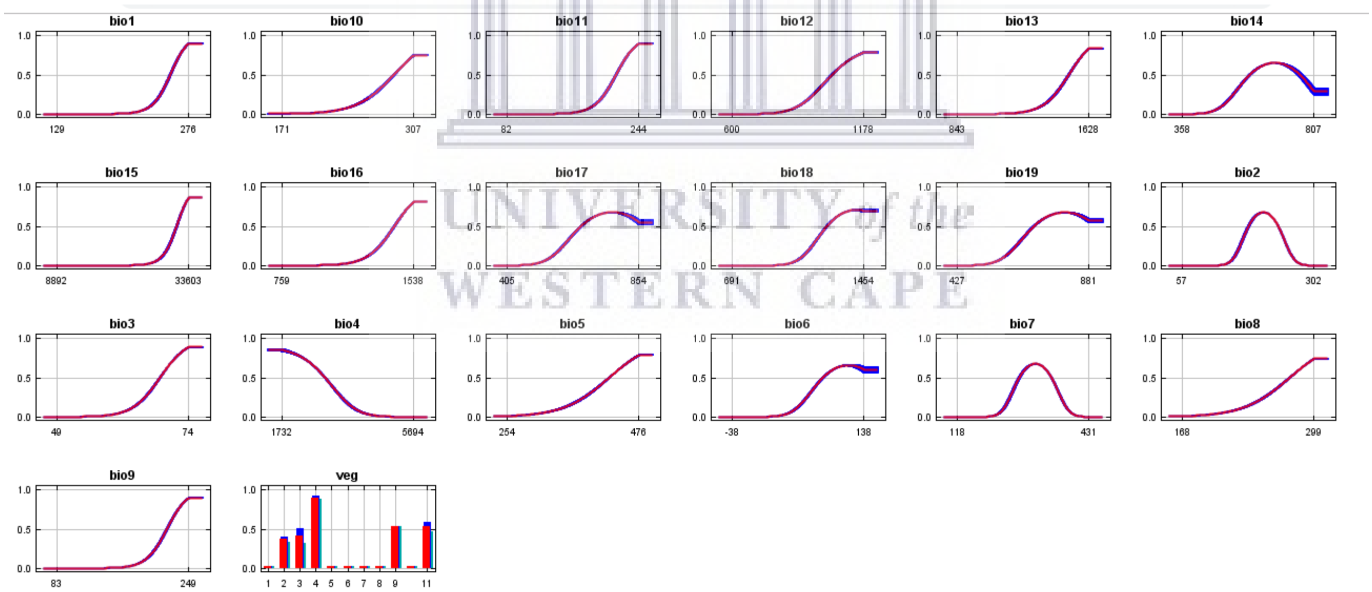

Figure 91: Alternative response curves for the Saddle Billed Stork

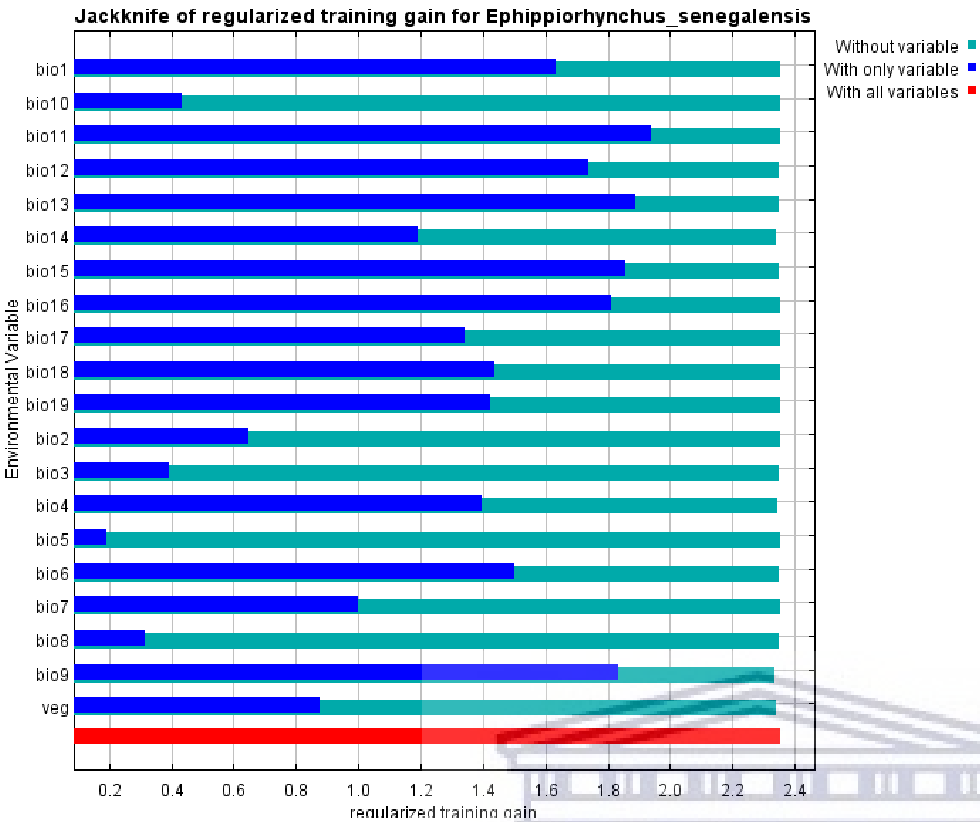

Figure 92: Jackknife of regularized training gain for the Saddle Billed Stork

Table 31: Analysis of variable contribution for the Saddle Billed Stork

Variable	Percent contribution	Permutation importance
bio13	21.1	20.2
bio3	14.8	0.2
bio16	13.2	0.3
veg	10.2	0.5
bio15	9.4	6.7
bio9	5.5	3.4
bio6	4	13.1
bio17	3.3	0
bio11	3	5.1
bio12	2.8	10.4
bio1	2.2	0
bio5	2	0.1
bio19	2	0.1
bio14	1.7	5.8
bio8	1.5	7.5
bio18	1.3	0.1
bio10	1	3.4
bio4	0.8	23.1
bio7	0.2	0.2
bio2	0.1	0

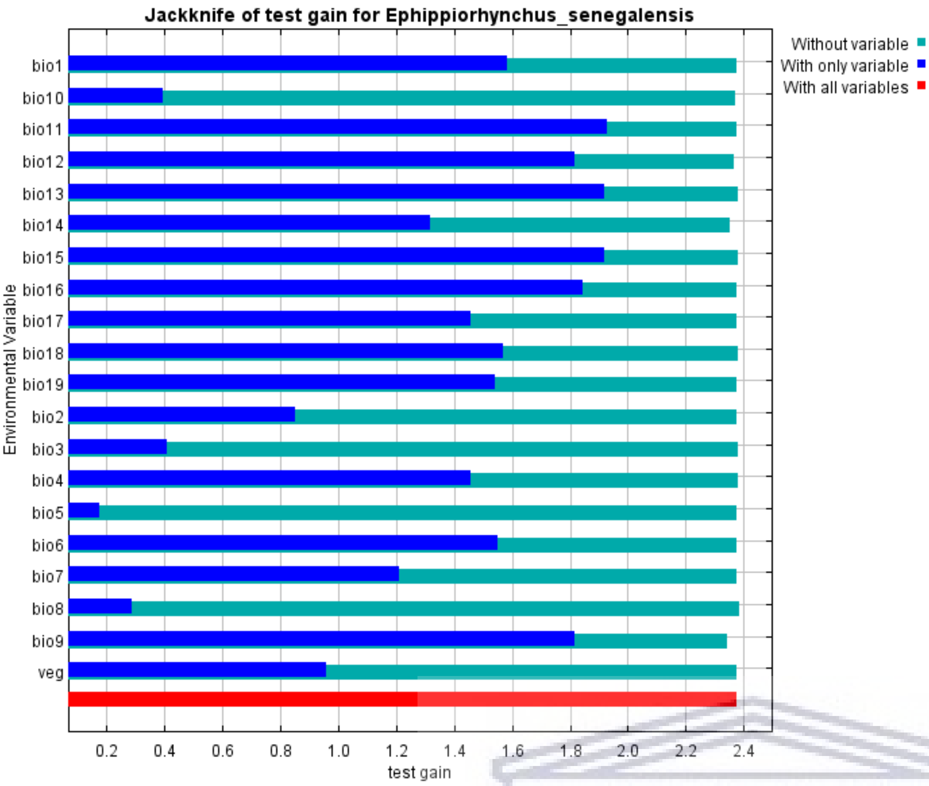

Figure 93: Jackknife of test gain for the Saddle Billed Stork

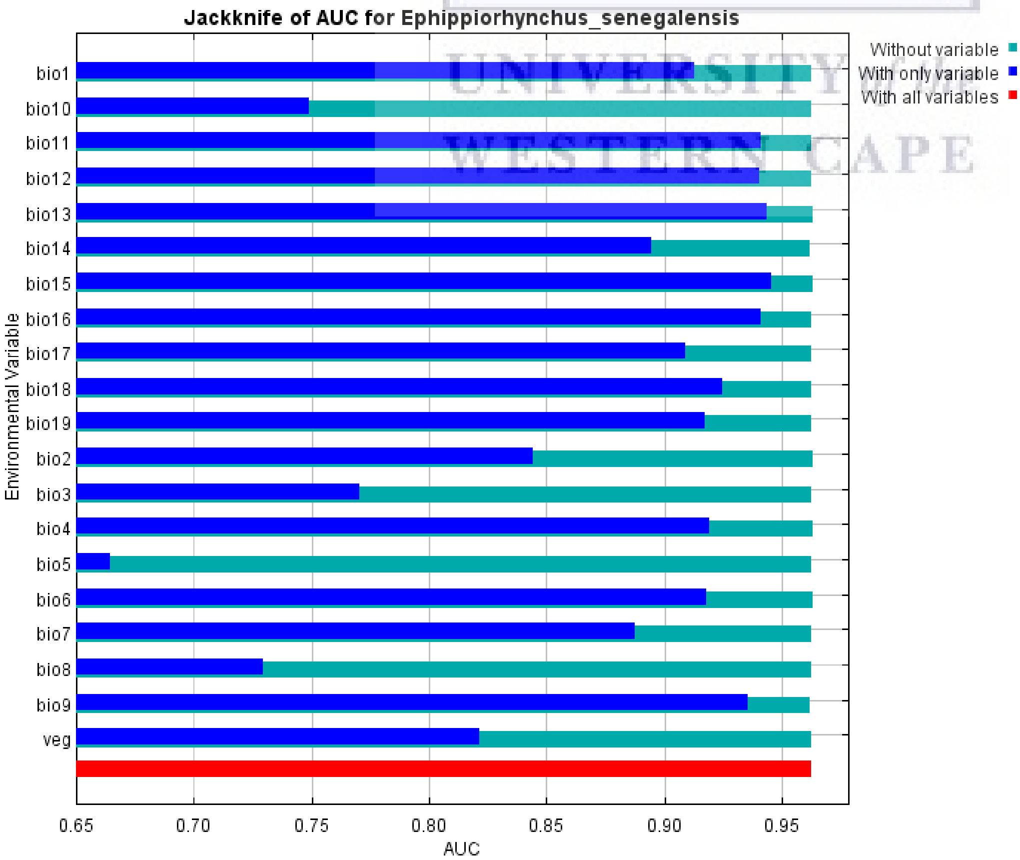

Figure 94: Jackknife of AUC for the Saddle Billed Stork

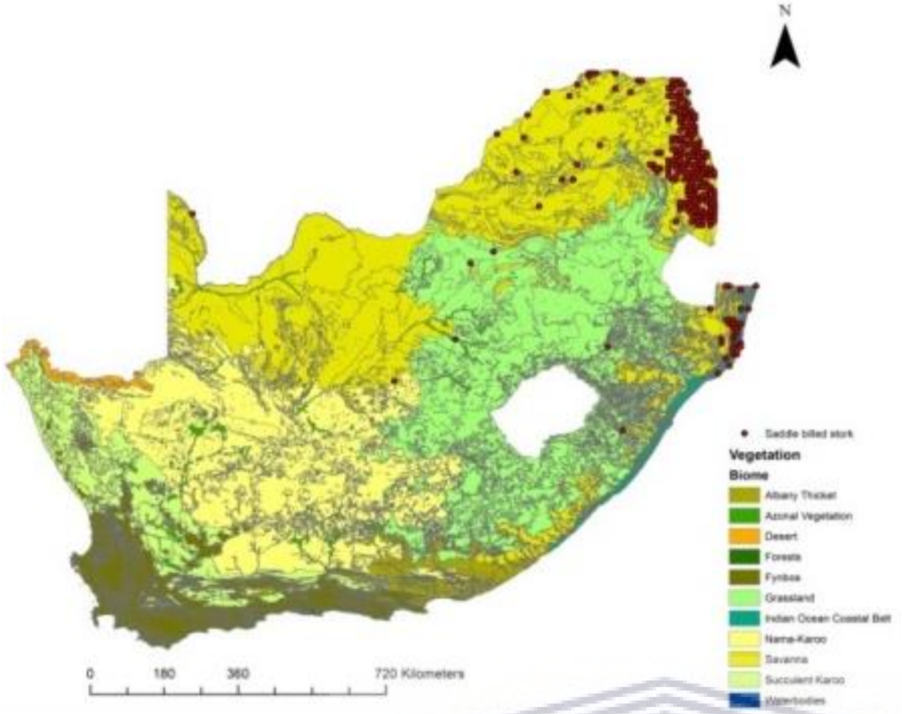

Figure 95: Saddle Billed Stork point distributions across the 11 vegetation biomes

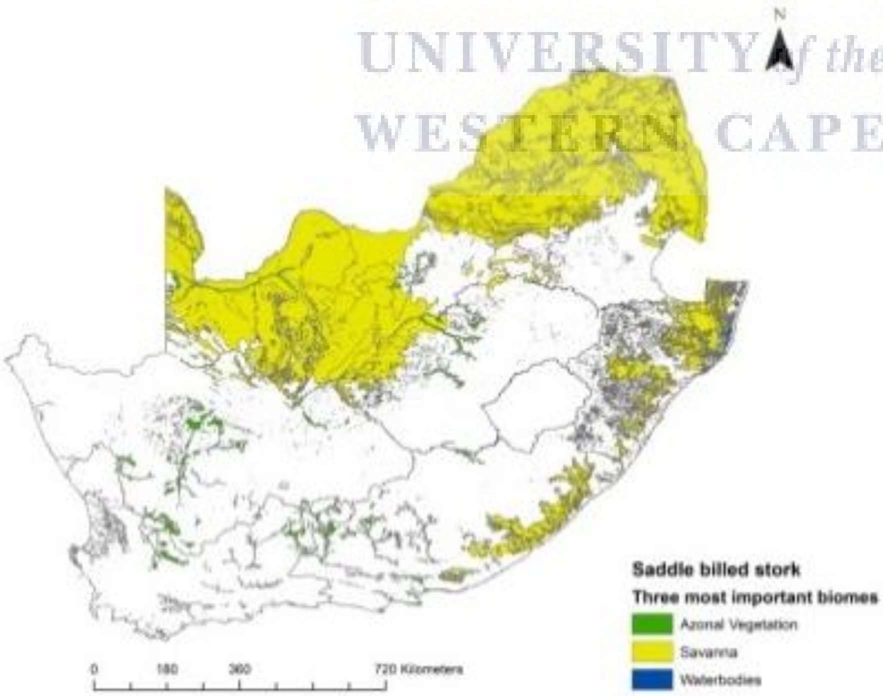

Figure 96: The three most important biomes for the Saddle Billed Stork according to MaxEnt

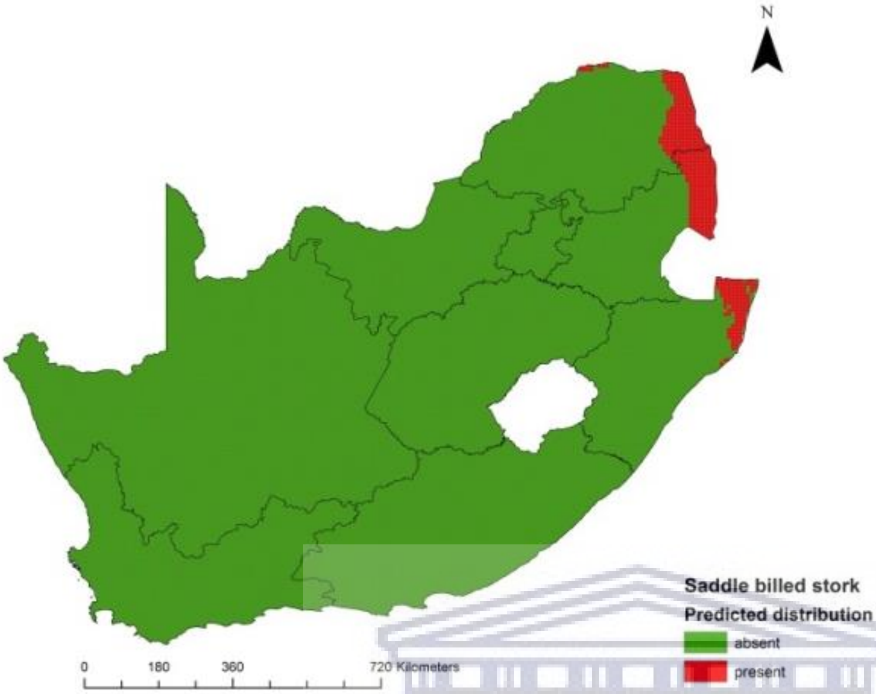

Figure 97: Predicted areas of presence according to MaxEnt for the Saddle Billed Stork

Wattled Crane

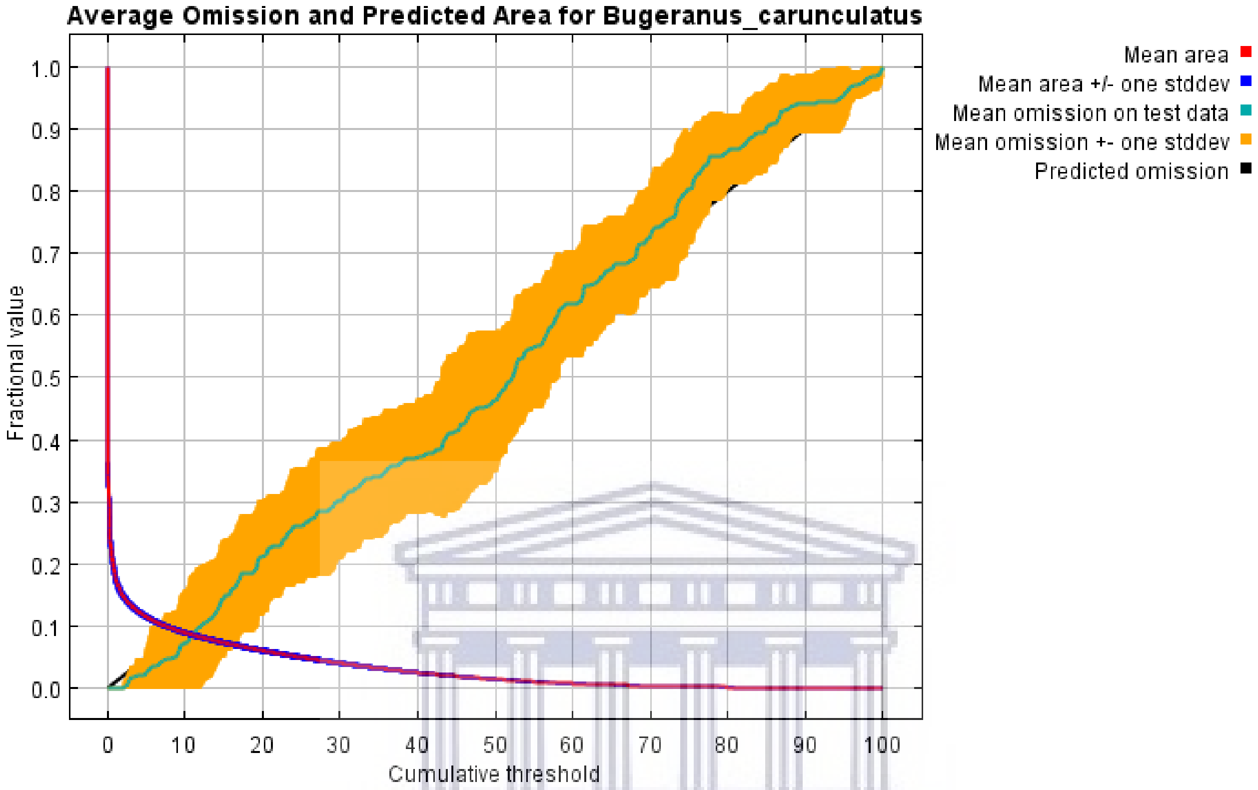

Figure 98: Average Omission and Predicted area for the Wattled Crane

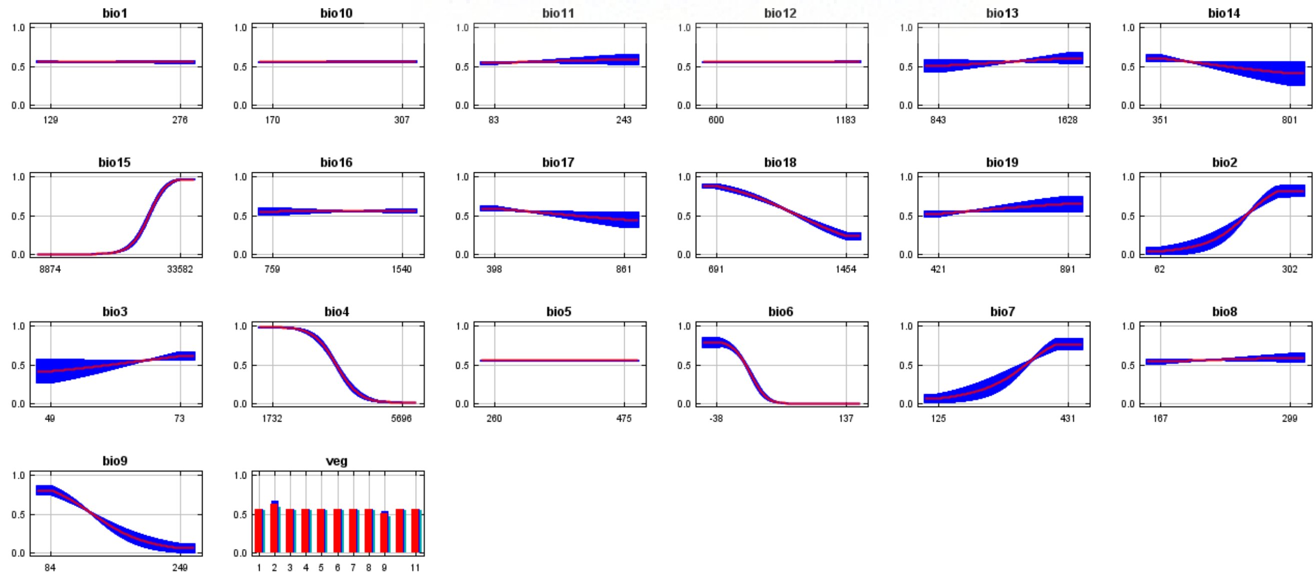

Figure 99: Marginal response curves for the Wattled Crane

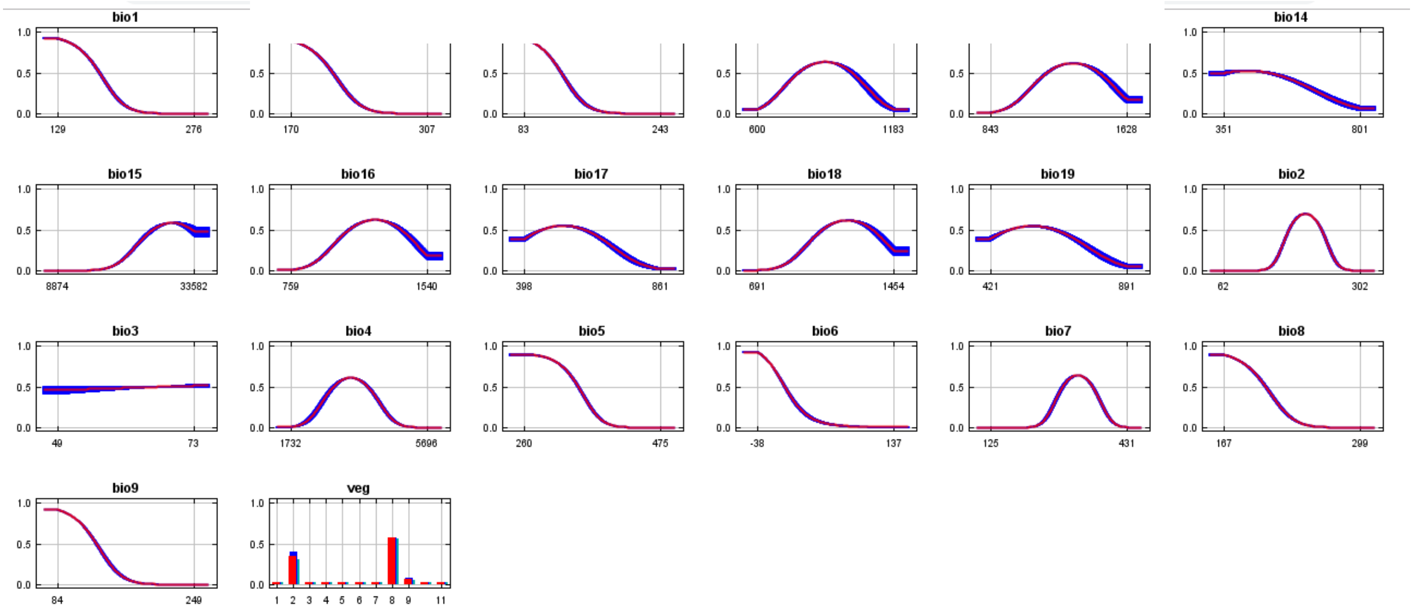

Figure 100: Alternative response curves for the Wattled Crane

Table 32: Analysis of variable contribution for the Wattled Crane

Variable	Percent contribution	Permutation importance
veg	25.5	0.1
bio10	23.4	0
bio8	11.2	0
bio4	8.3	24.8
bio1	6	0
bio15	5.4	40.1
bio5	4.2	0
bio7	3.5	0.7
bio6	3	27.6
bio9	1.9	3.5
bio3	1.9	0
bio11	1.1	0
bio18	1.1	1.6
bio19	0.7	0.1
bio17	0.7	0.1
bio13	0.6	0.1
bio16	0.6	0
bio2	0.5	1.2
bio14	0.3	0.1
bio12	0.1	0

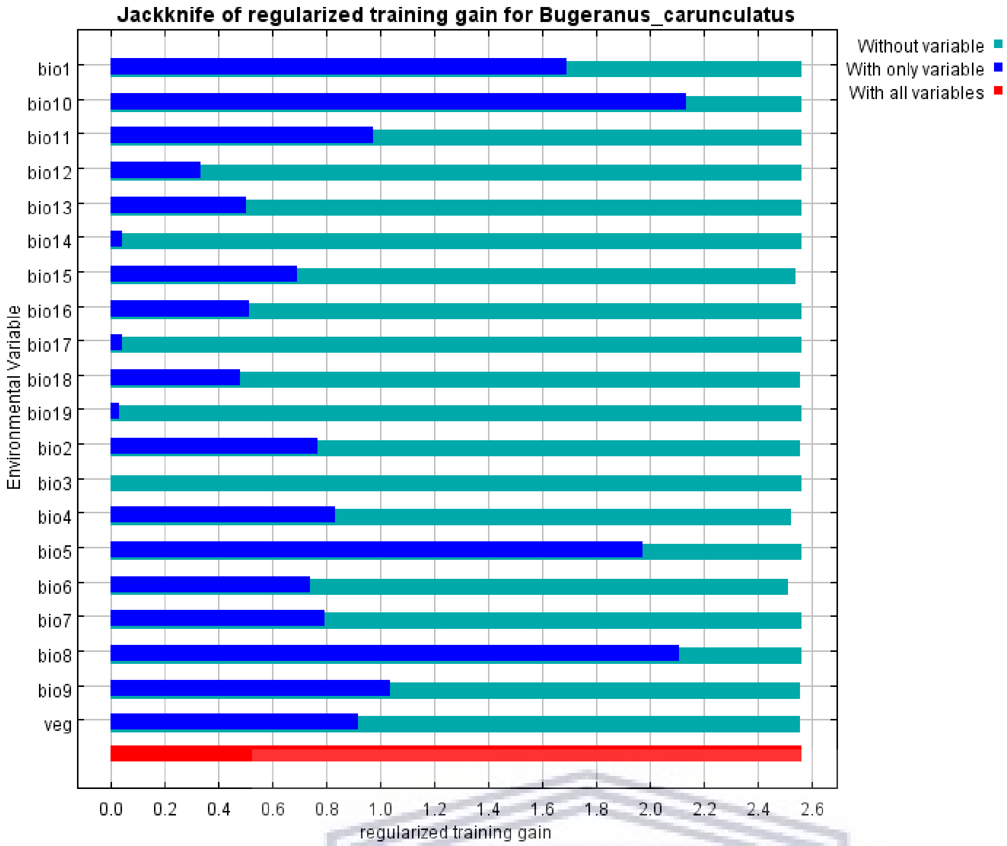

Figure 101: Jackknife of regularized training gain for the Wattled Crane

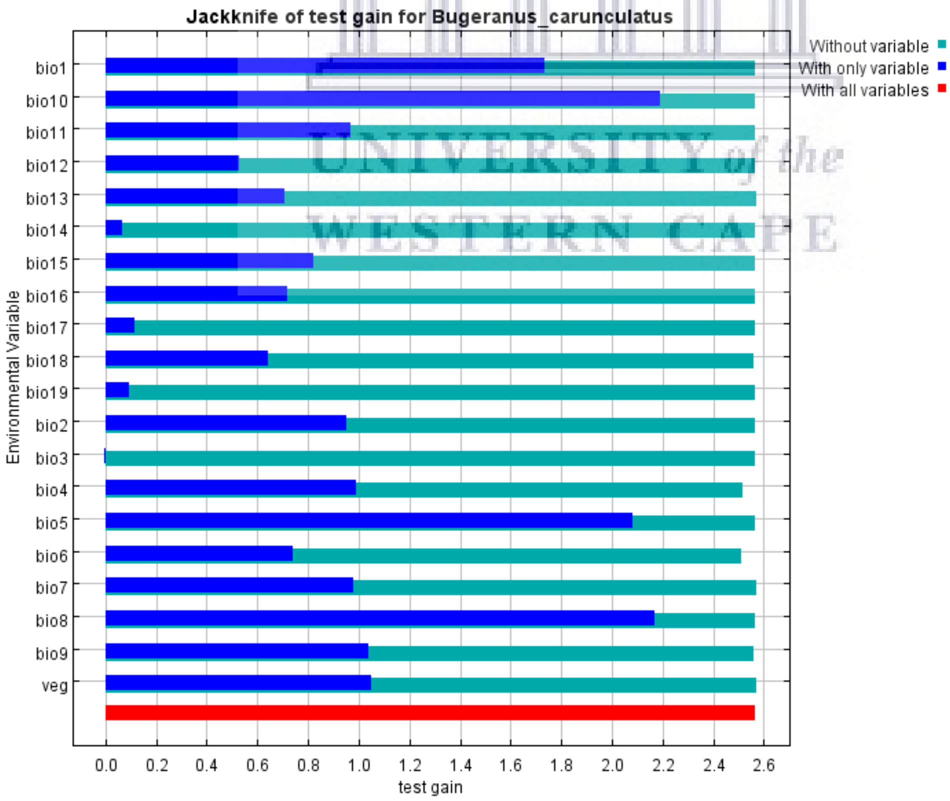

Figure 102: Jackknife of test gain for the Wattled Crane

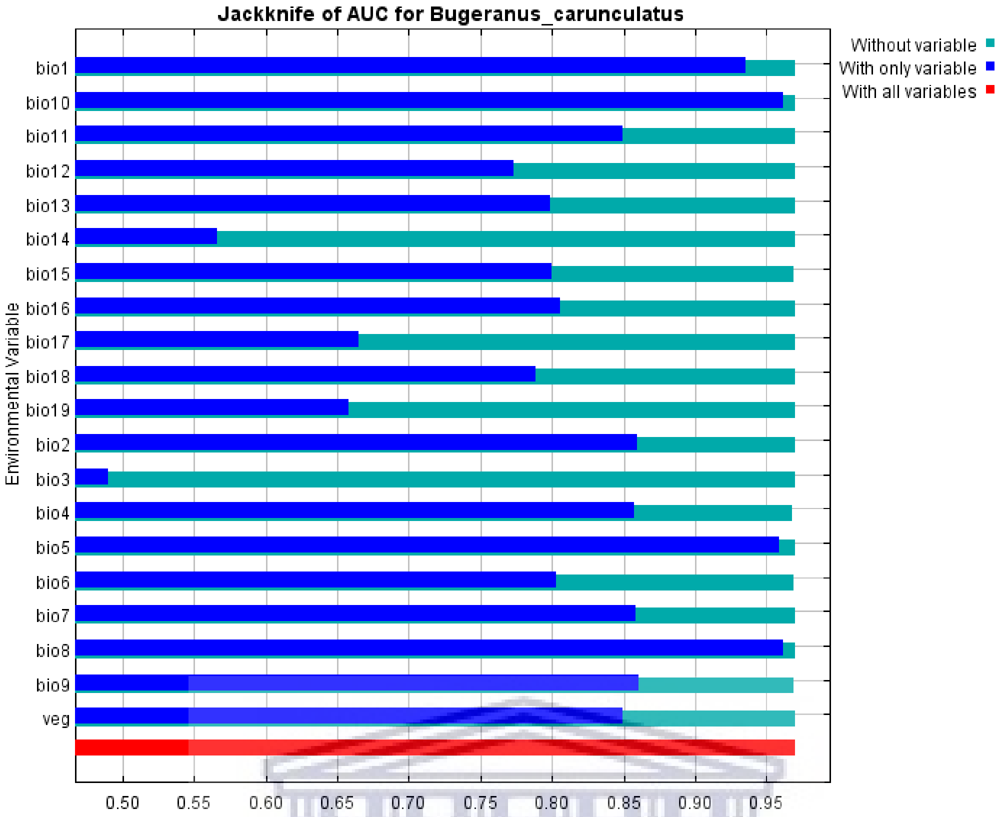

Figure 103: Jackknife of AUC for the Wattled Crane

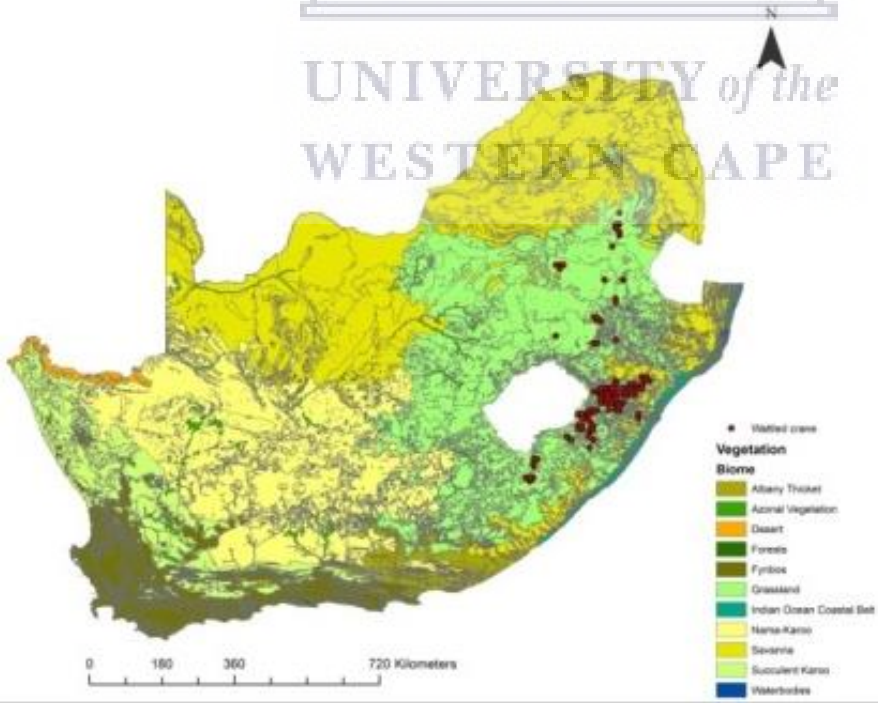

Figure 104: Wattled Crane point distributions across the 11 vegetation biomes

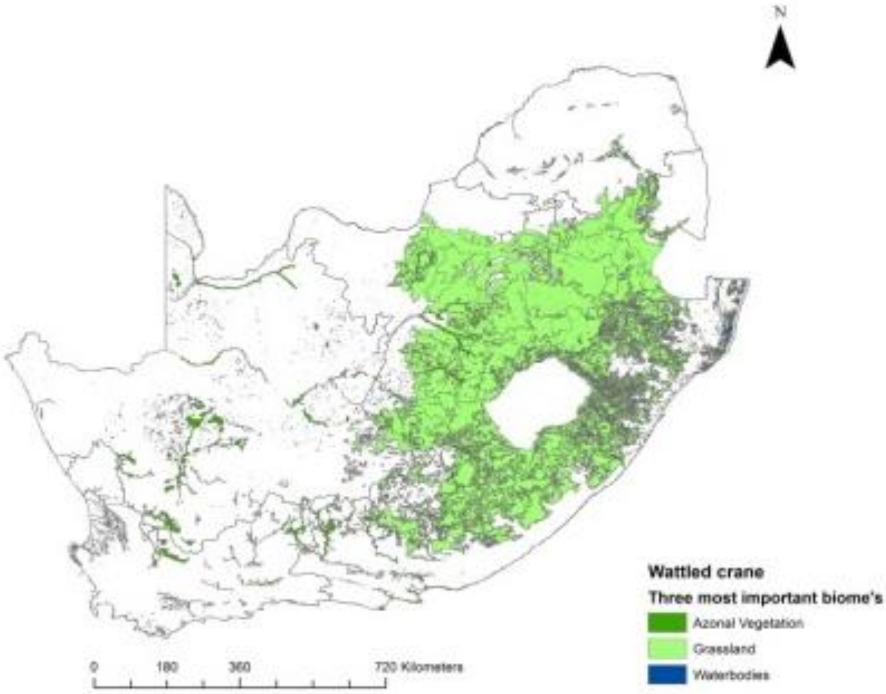

Figure 105: The three most important biomes for the Wattled Crane according to MaxEnt

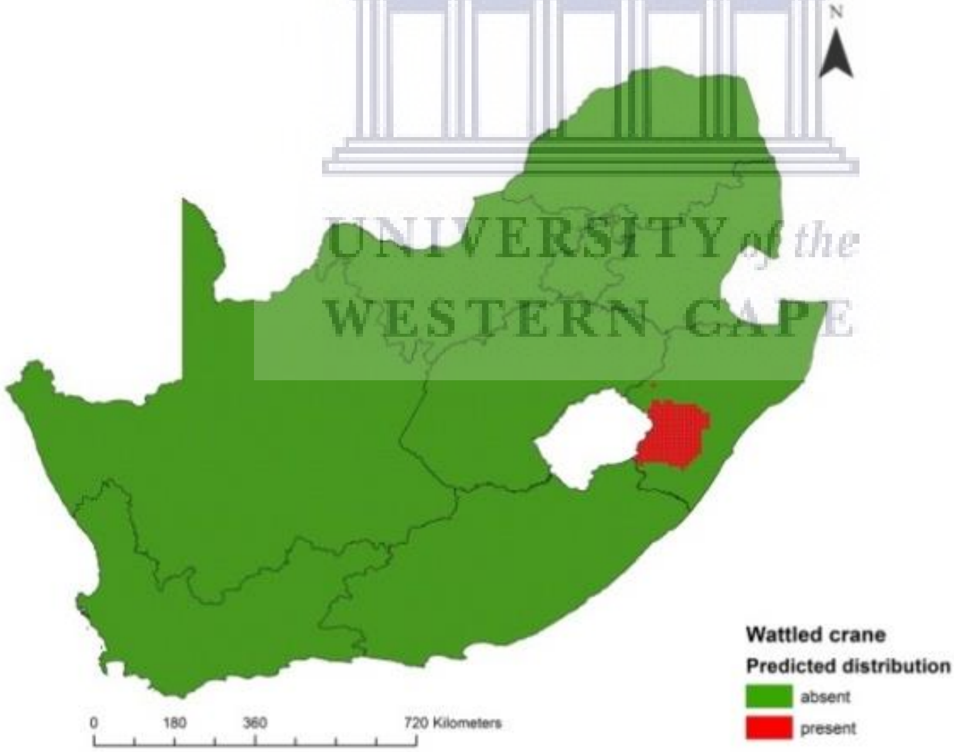

Figure 106: Predicted areas of presence according to MaxEnt for the Wattled Crane

Yellow Billed Stork

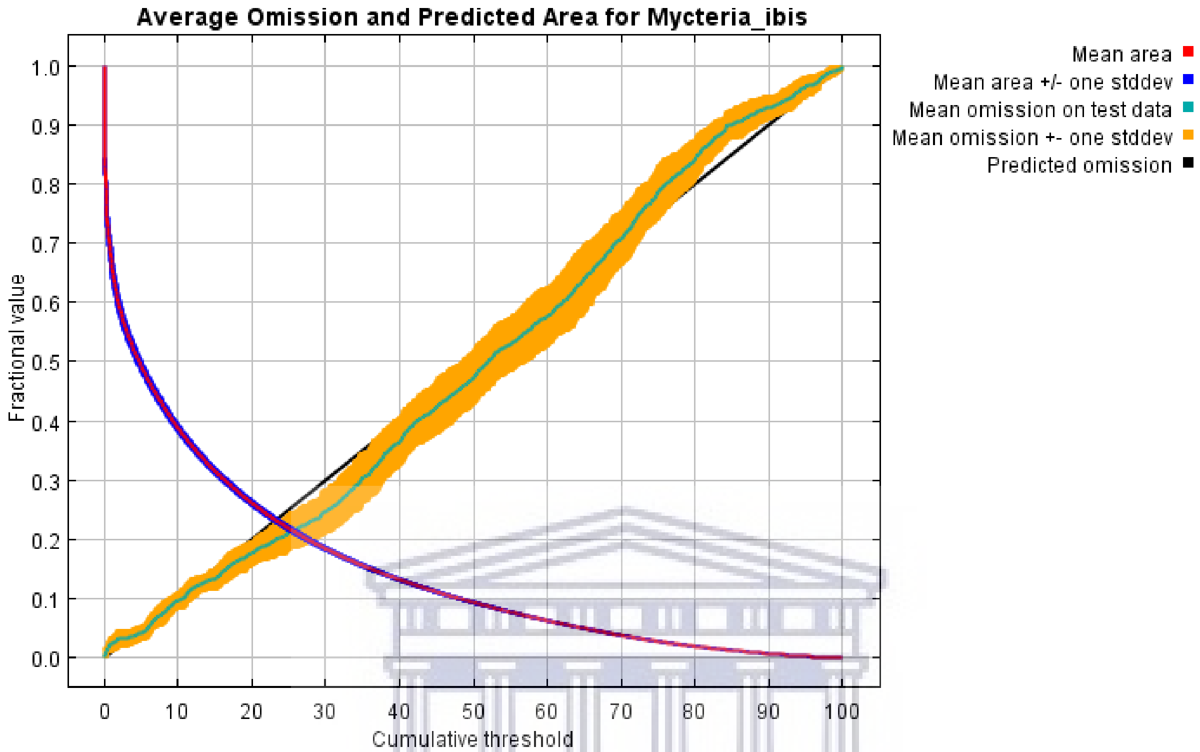

Figure 107 : Average Omission and Predicted area for the Yellow Billed Stork

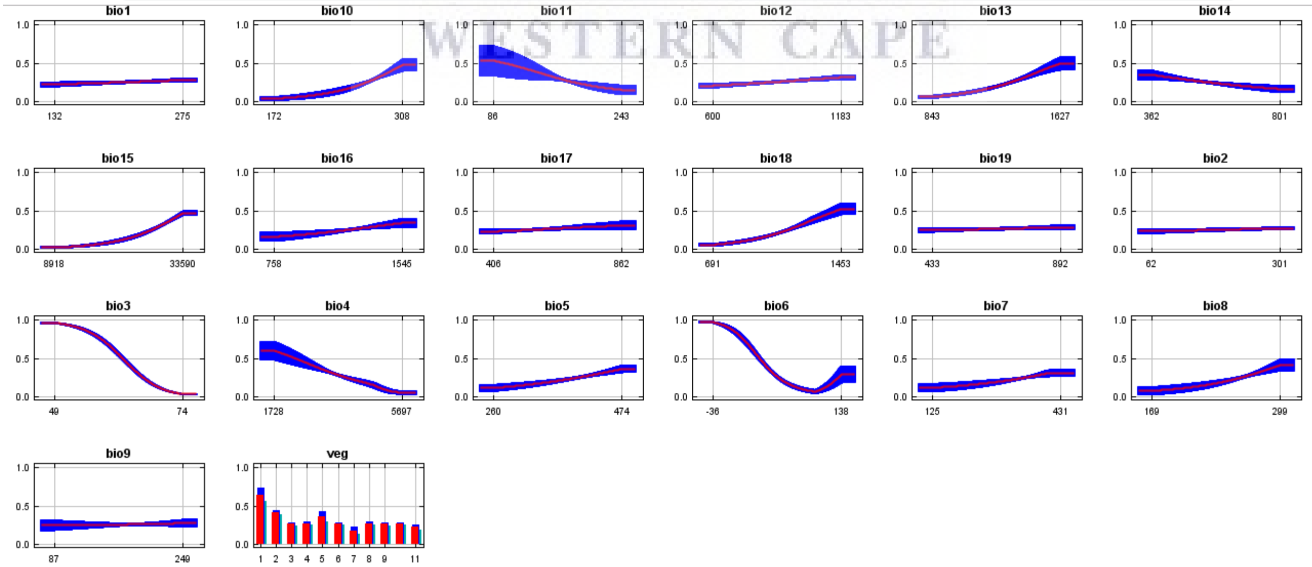

Figure 108: Marginal response curves for the Yellow Billed Stork

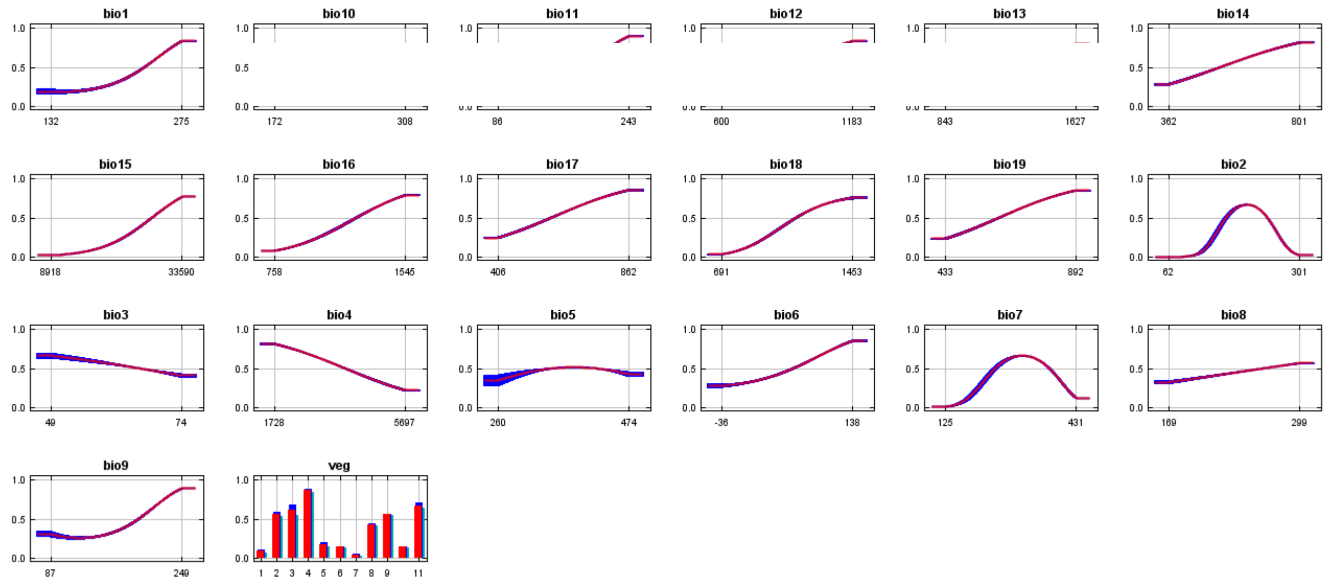

Figure 109: Alternative response curves for the Yellow Billed Stork

Table 33: Analysis of variable contribution for the Yellow Billed Stork

Variable	Percent contribution	Permutation importance
bio13	25.8	11.8
bio15	14.5	15.4
veg	10.4	3.2
bio6	8.6	14
bio4	8.1	11.7
bio16	7.5	2.8
bio3	4.8	9
bio12	3.4	0.6
bio18	2.6	10.2
bio10	2.3	9.3
bio8	1.7	5.9
bio11	1.7	2.4
bio1	1.6	0.1
bio17	1.4	0.6
bio9	1.4	0.4
bio19	1.3	0.1
bio5	1.2	1
bio7	0.8	0.5
bio14	0.6	0.8
bio2	0.3	0

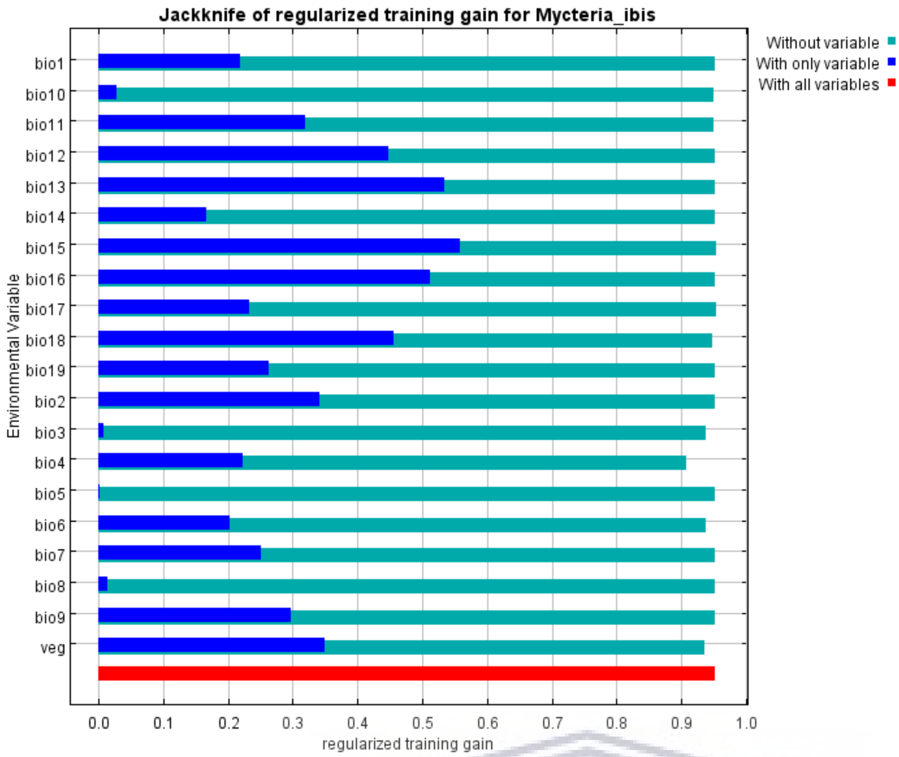

Figure 110 : Jackknife of regularized training gain for the Yellow Billed Stork

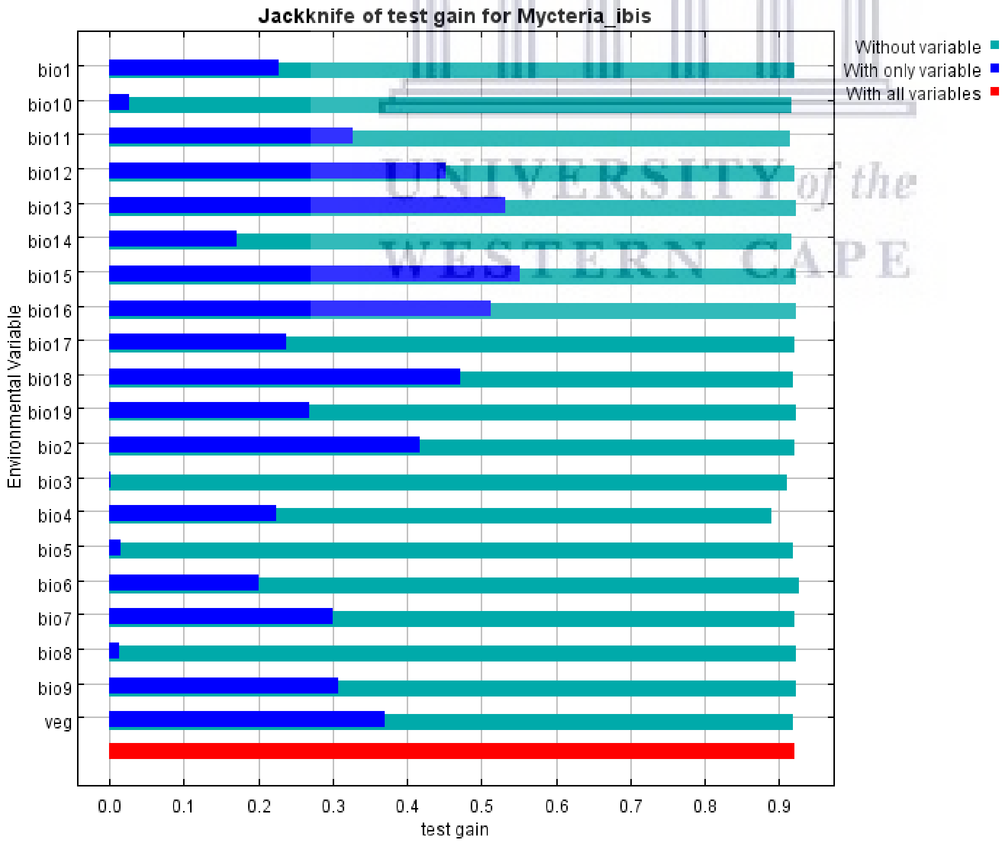

Figure 111: Jackknife of test gain for the Yellow Billed Stork

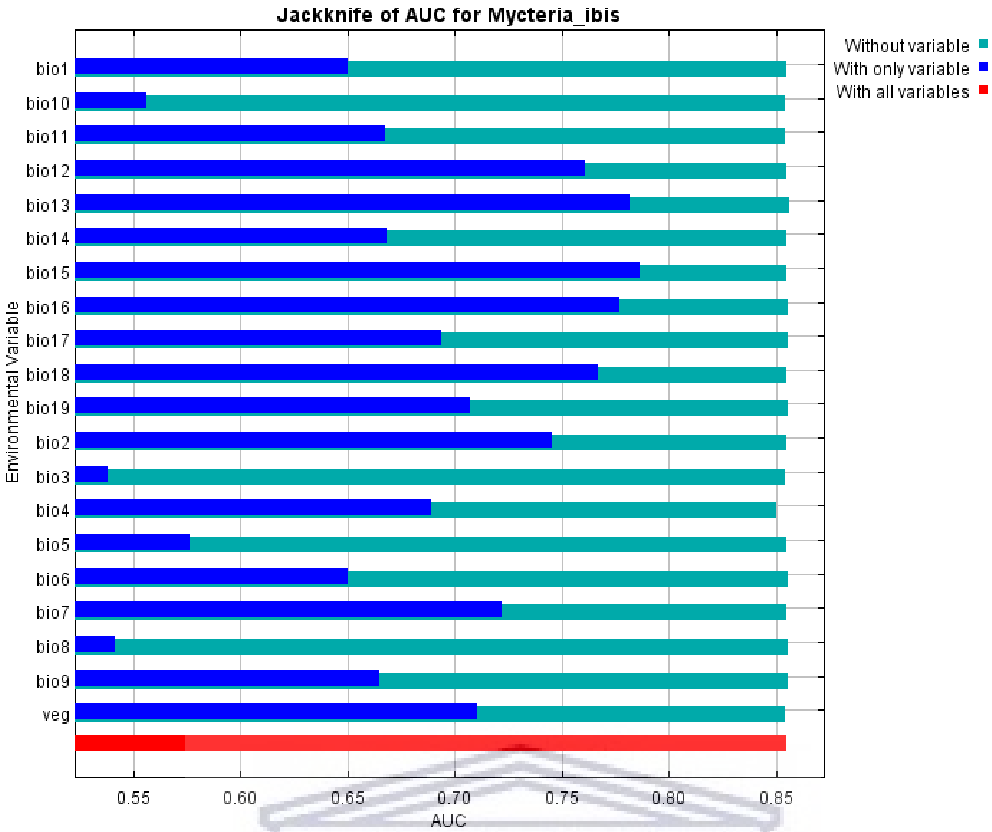

Figure 112: Jackknife of AUC for the Yellow Billed Stork

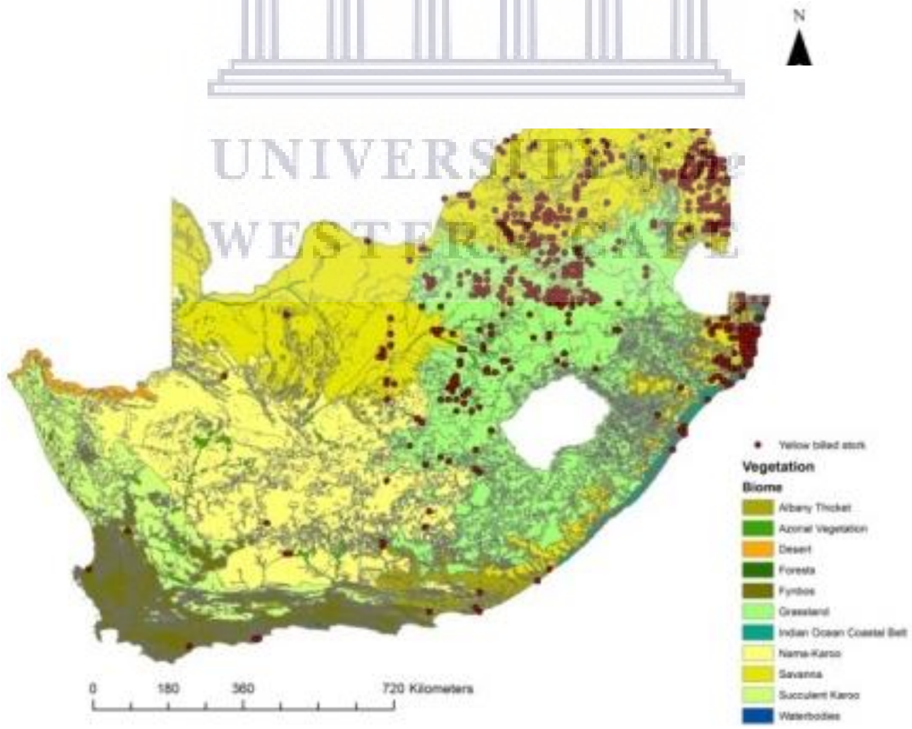

Figure 113: Yellow Billed Stork point distributions across the 11 vegetation biomes

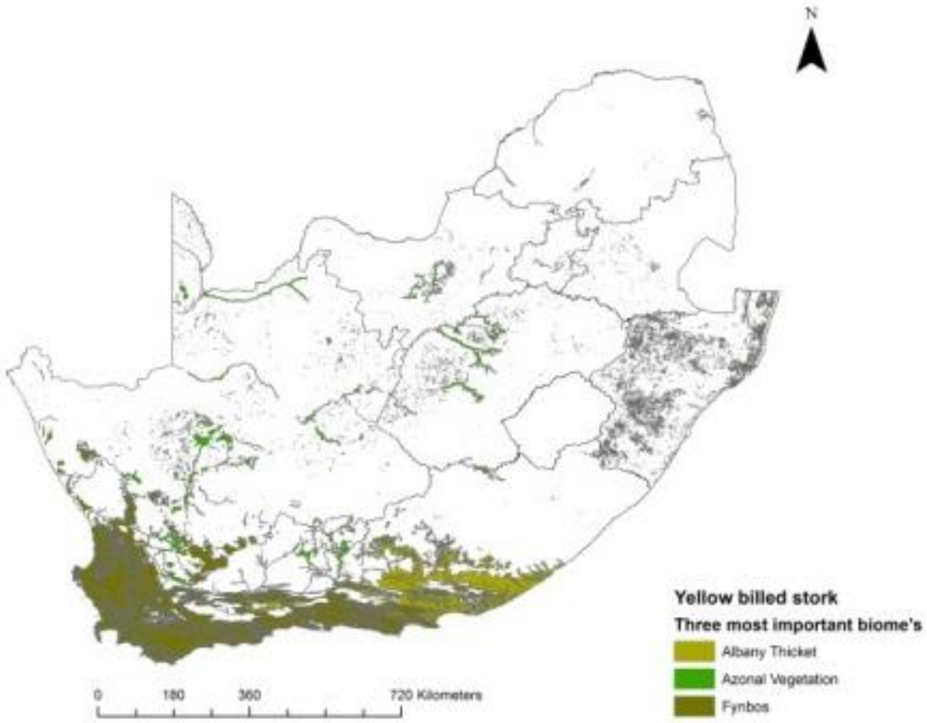

Figure 114: The three most important biomes for the Yellow Billed Stork according to MaxEnt

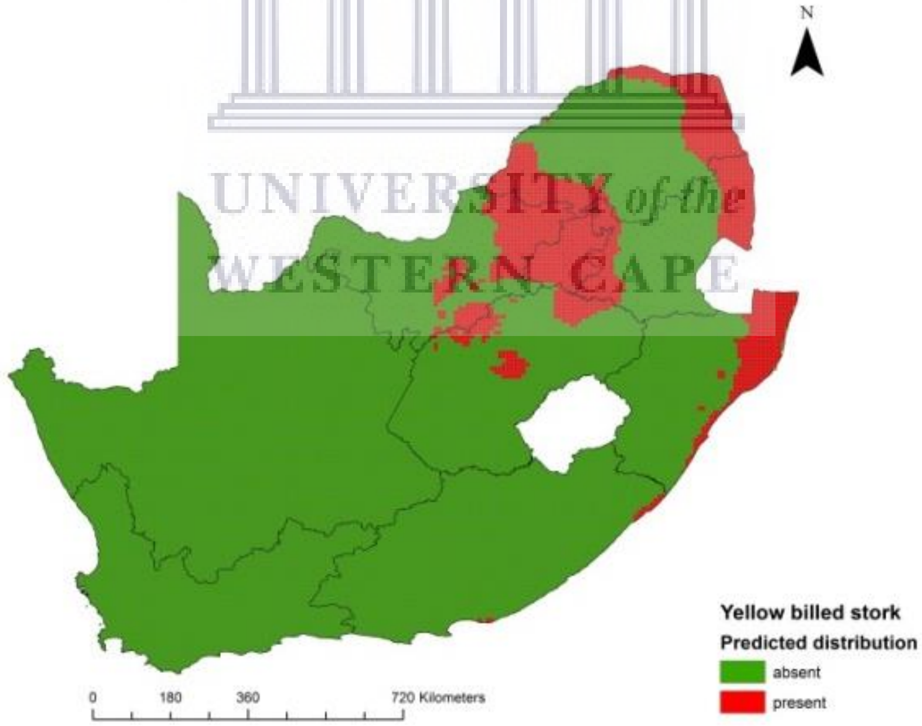

Figure 115: Predicted areas of presence according to MaxEnt for the Yellow Billed Stork