ELUCIDATING THE DRIVING FACTORS OF EXTINCTION RISK OF GLOBAL CYCAD SPECIES

by

GREGOIRE KANTAKWA SADIKI

submitted in accordance with the requirements for

the degree of

MASTER OF SCIENCE

in the subject

ENVIRONMENTAL SCIENCES

at the

UNIVERSITY OF SOUTH AFRICA

SUPERVISOR: DR KOWIYOU YESSOUFOU

APRIL 2021

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX

DECLARATION

I, Sadiki (61657573), hereby declare that this dissertation submitted at the University of South Africa is my own work and has not been submitted before at this or another institution for qualification.

GREGOIRE KANTAKWA SADIKI

April 2021

DEDICATION

This work is dedicated to the memories of:

My father **Férdinand-Berthold Sadiki**,

My uncles **Stéphane** and **François Sadiki**,

My brothers **Férdinand Jr** and **Jérôme Sadiki,**

My sister **Martha Sadiki,**

They all passed on very early without even see the achievement of this present study.

“Cycads are to the vegetable kingdom what Dinosaurs are to the animal, each representing the culmination in Mesozoic times of the ruling Dynasties in the life of their age.”
Lester Ward, 1900

ACKNOWLEDGEMENTS

Numerous people have directly or indirectly contributed through direction, encouragements or motivation to guarantee the success of my study, and they all deserve my gratitude.

I have to start by expressing my gratitude to Dr Kowiyou Yessoufou, who is the main supervisor of this study. I have been blessed to having him; his guidance and support towards the success and completion of my research have exceeded my expectations.

I really owe an enormous amount of thank to the personnal of the main library of the University of South Africa with their gentleness and friendless by making available books as well as some electronical articles I needed for my dissertation.

Special thanks go to my two brothers Coco Sadiki (a Dr in his own right) and Jacques Sadiki for believing in my capacities from the very beginning and ensuring that I become the Master degree holder in the Sadiki family tree.

Thanks to my unforgettable friends Dr Junior Bolukaoto, Dido Tumba and Christian Lueme for making me familiar with research environment by showing academic orientations that I could not reach by myself.

I would also like to give a special thank to Dr Alain Kamika; through him, I have met for the first time my supervisor.

My gratefulness goes to Mr. Prevost Paluku, Etienne Kiyiro, Tabin Mupenda, Dieu Wawina, Prudent Lingombi, Edouard Liwaka, Jean-Louis Mwandika, Etienne Melly, Oscar Salumu, Jacques Andia, André Bwandola, Bezo Zinde, Dr Jr Tshiamala, Dr Anaclet Omari, Maître Tresor Lotemba, Dr Patou Ayikwa and Dr Jeremy Mitonga for their words of encouragement. I do thank Ms. Isabelle Ngandi, Dr Evelyne Bafandu Sadiki, Desiré Musondivwa, Mrs Emilienne Yohali Sadiki, Junior Mafwila, Anthony Obendo, Patient Lofalata, Samuel Kandolo, Jeannot Lingela, Dr Serge Mpiana, Dr Marlin Mpiana, Dr Achille Mubiayi, Axel Ali, Christine Litifo, Dr Gracia Bolukaoto, Papy Tokombe, Yves Tokombe and Rachidi Mawete for their solid supports.

My colleagues at the University of South Africa, namely Gracia Kamika, Ir. Joseph Litua, Emmanuël Mbuyi, Irène Kobo-Muwampi, Christine Foma, Michel Kana, Dr

Katumba, Pastor Bolingo, Alice ODU, Nadine Kisema, Marcel Mangu, Dr Daniel Ndombo and Dr Pascal Kiabula are hereby acknowledged for their inspiration and sincere companionship.

My mothers Christine Masunga and Honorine Nyota, as well as my uncles Elias Sadiki, Gaston Agigi and Demokos Mekodjo are hereby acknowledged.

I would also like to thank all my brothers and sisters in the Sadiki family tree. Let the achievement of this dissertation serve as proof of what we are able of realizing in our family.

Finally, I give all thanks to the Almighty God for the gift of life, strength and His abundant grace upon my life. To Him are all the magnificence, honour and worship.

God bless you all.

ABSTRACT

Biodiversity is rapidly declining worldwide because of the anthropogenic impacts on the environment regarding goods and services it delivers to humanity. Evidence suggests that we have entered the period of sixth mass extinction of human history. Being interested in distinguishing the pre-disposition of cycads to such risk of extinction, integration of structural equation modelling (SEM) on cycads was used. This plant belongs to a gymnosperm group, which exhibit the highest rate of extinction in the plant kingdom. This present study aimed to inform conservation decision-makers to be aware of the factors that drive the extinction risk of cycad species. The specific objective was to formulate and test a meta-model that explains the patterns of the extinction risks of cycads. However, several groups of threats to cycads were identified and the most prominent were those connected to human activities. Likewise, some variables that correlate with the extinction risks of cycad species were classified. Then, a cycad phylogeny was used to calculate ED values for each species so that high–ED species were those that merit specific attention. Nevertheless, *Microcycas calocoma* was the species having the highest ED score (98.762 MY). By using SEM, the results demonstrated a negative but significant relationship between ED and maximum height (β= -0.1226; SE= 0.0439; P = 0.0076). Moreover, the findings further demonstrated significant relationships between other variables and the positive ones were maximum altitude with generation time, range with maximum height and maximum altitude with number of threats. Therefore, maximum height with generation time has a significant but negative relationship. Thus, maximum height and generation time are variables considered as best predictors for extinction risk in cycad species, with a projecting power of 99% and 48% respectively. This work is best suited to inform conservation decisions regarding the rapid loss of cycads through human activities. Therefore, we recommend decision-makers to design a bigger picture for a conservation plan on cycad species (especially those having high-ED values), to prevent their extinction; implement the legislation and regulation of human-cycad connections.

Keywords: Anthropogenic activities, mass extinction, species loss, IUCN, evolutionary distinctiveness, structural equation modelling.

LIST OF ABBREVIATIONS

AIC	Akaike information criterion
ANOVA	Analysis of variance
BIC	Bayesian information criterion
BMP	Biodiversity management plans
CBC	Community-based conservation
CITES	Convention on international trade in endangered species
cm	centimeter
CR	Critically endangered
DD	Data deficient
df	degree of freedom
DNA	Desoxyribonucleic acid
ED	Evolutionary distinctiveness
e.g.	Exampli gratia (For example)
EN	Endangered
***et al*.**	and others
etc.	et cetera (‘and the other things’)
IUCN	International union for the conservation of nature
km	kilometer
km^2	squared kilometer
LC	Least concern
MCMC	Monte Carlo Marcov Chain

NEMBA	National Environmental Management Biodiversity Act
m	meter
matK	maturase K
MY	Million years
Mya	Million years ago
nrITS	Nuclear international transcribed spacer
NT	Near threatened
NA	not applicable
NPA	natural protected areas
PAUP	Phylogenetic analysis using parsimony
PHYP	Phytochrome P
PD	Phylogenetic diversity
psbA-trnH	Spacer between the trnH and psbA genes
rbcLa	Subunit "a" of Ribulose 1,5-Biophosphate Carboxylase/Oxygenase
SSC	Species survival commission
SE	Standard error
SEM	Structural equation modeling
VU	Vulnerable
≥	greater or equal to
≤	less than or equal to
=	equal
β	Beta

CHAPTER 1
INTRODUCTION AND RESEARCH BACKGROUND

1.1 Introduction

Global biodiversity is rapidly declining because of the ongoing and increasing anthropogenic impacts on the environment (Wilting *et al*., 2017) and many sources indicate the loss of biodiversity at an exceptional rate (Millennium Ecosystem Assessment, 2005; Vamosi and Vamosi, 2008). The future of humanity depends on the goods and services from biodiversity such as food production, clean water, climate stability, medicinal plants, plant pollination, nutrient cycling, clean air, carbon sequestration, recreation and tourism, etc. (Millennium Ecosystem Assessment, 2005) provided by a well-functioning structure of biological diversity (Yessoufou and Davies, 2016). Unfortunately, this need might bring the loss of these ecosystem goods and services on a particular concern (Millennium Ecosystem Assessment, 2005). The risk of species extinction is linked in several ways to human population growth and activities including habitat destruction, invasive alien species and over-exploitation (Harberl *et al.,* 2007; Winter *et al.,* 2009; Willis *et al.,* 2010), as well as climate changes (Millennium Ecosystem Assessment, 2005). Dirzo and Raven (2003) asserted that the loss of biodiversity is the one irreversible global environmental aspect that can change the face of our earth today.

However, climate change, for instance, is predicted to be a main driver of extinction in the future of biodiversity, due to intervals in the ability of species to adjust their physiology and life histories (e.g. phenology, abundance, distribution and interaction, etc.) to match the new climate regime (Willis *et al.,* 2010; Cahill *et al.,* 2012). A study of the International Union for the Conservation of Nature (IUCN) projected that climate change could drive a quarter to one-half of world's land (animals and plants included) to loss by the end of this century (IUCN, 2010; Foden *et al.,* 2013; Miller and Spoolman, 2017). However, at the international policy target of a 2^{o}C post-industrial rise, which experts now agree is no longer achievable, global extinction risks have increased from 2.8 to 5.2% at present (Fuss *et al.,* 2014). Nonetheless, if the earth warms to 3°C, the extinction risk will rise to 8.5% which means that climate change will threaten one in six species globally (16%) then it could distress ecosystems and the services they provide to humans (Lawler *et al.,* 2009). A good example is coral reefs, which could be missing in the next century if global warming continues at the current tendency (Kannan and James, 2009). The signal of climate change-induced extinctions will become progressively more apparent if there is no action to limit future climate change (Urban, 2015).

In the period from 1950 to 2011, worldwide people increased from 2.5 billion to 7 billion (Visconti *et al*., 2015) and the expectation shows that human population will show an exponential growth to reach 9.8 billion by 2050 (United Nations, 2004). Indeed, current predictions put the possible number of people on the planet at 11 or 15 billion by 2100 (Gerland *et al.,* 2014). Consequently, that growth will exert pressure on natural resources and will continue to drive extinctions within a short period (Baillie *et al*. 2004; Pullaiah *et al.,* 2015). Potentially, it could decrease the provisioning of service deliveries (i.e. species and biodiversity particularly in the Tropics) (Vamosi & Vamosi, 2008; Archard *et al*., 2002; Wake and Vredenburg, 2008) at the time when demand is growing, as conflict between human development and wildlife still ongoing (Santini *et al.,* 2016). The elevated rates will be in tropical biomes particularly, which are known for their unique life-form diversity (Vamosi and Vamosi, 2008). However, there is an expectation that the future rate of species extinction could be raised by at least a further order of greatness over the next few hundred years (Tafirei, 2016). Nevertheless, that extinction rate differs from one species to another, which makes a pattern referred to as non-random extinction (Yessoufou and Davies, 2016). Pullaiah *et al.* (2015) demonstrated that world could lose more than a million species of plants and animals during the next 20 to 30 years, principally because of environmental changes due to human activities. These activities continue to be the main risk to species diversity and long-term survival (Volis, 2016). Consequently, it is a matter of urgency to understand how the ongoing extinction crisis will affect the provisioning of critical ecosystem services (Yessoufou and Davies, 2016).

In their recent work, Miller and Spoolman (2017) demonstrated that the past five mass extinctions have been caused by abiotic factors like asteroid airstrikes and volcanic eruptions in natural climate shifts. For now, scientists agree that we are in the sixth mass extinction period of human history (Magurran and Dornelas, 2010;

Barnosky *et al*., 2011; McLellan *et al.,* 2014). Humans (Anthropogenic period) are now causing this current sixth mass extinction through the co-option of resources, the spread of pathogens, the destruction of habitats, the introduction of non-native species and changing global climate (Barnosky*,* 2009; Vredenburg *et al.,* 2010). Pievani (2014) confirmed that we are not yet exactly in the middle of the sixth mass extinction, but then the rate is higher than caused by abiotic factors. Cafaro (2015) summarized three possible ways to think about the sixth mass extinction, such as i) the loss of important resources (as error), ii) interspecies genocide (as crime), and ii) the evidence that humanity is cancer on the biosphere (as inevitability). He then mentioned that this mass extinction of Earth's biodiversity is irresponsible and representing a serious mistake, that humanity will come to regret.

However, the recent rate of species loss might be 1,000 to 10,000 times greater than observed in the past extinction (Millennium Ecosystem Assessment, 2005; Pullaiah *et al.,* 2015) and most species on Earth would be eliminated within 100 years at this current rate of loss (Miller and Spoolman, 2017). The IUCN in 2010 reported that amphibian species are the most at risk among vertebrates with an average of 41% to be threatened, and that estimation showed how much this species is facing an uncertain future. Nevertheless, 21% of fish are threatened with 20% of continental mammals, nearly 12% of the world’s bird species and 10% of temperate regions’ plants have already been lost (IUCN, 2010; Pullaiah *et al.,* 2015). Also, at the islands of tropical Oceania, up to 1800 bird species were estimated to have become extinct in the ~2000 years since human colonization (Ceballos *et al*., 2015). Kannan and James (2009) mentioned that destruction of habitat has played an important role in extinctions, particularly those related to Tropical Forest. Some factors that contribute to biodiversity's habitat destruction are over-consumption, over-population, land-use change, deforestation, pollution (air pollution, water pollution, soil contamination) as well as climate change.

As over 70% of flowering plants assessed globally are at risk of extinction (IUCN, 2010), suggesting that this proportion is much higher than the one reported to vertebrates (22%) and the risk of extinction is more worrisome. Conversely, existing knowledge indicates that biological or ecological factors and evolutionary history pre-dispose many taxonomic groups to the extinction risk (Davies *et al.* 2011; Yessoufou *et al.,* 2012). A better explanation is that traits history of existence like body size predispose vertebrates to the risk of extinction (Cardillo, 2003; Yessoufou and Davies, 2016) but for plant species, extinction risk is linked to their existing history than their evolutionary (Vamosi and Wilson, 2008; Daru *et al*., 2013). Besides, the evolutionary history of a species may be more important than its life history in the explanation of extinction risk (Yessoufou and Davies, 2016).

1.2 Global extinction crisis of cycads

Global biodiversity is rapidly declining because of the ongoing and increasing anthropogenic impacts on the environment (Wilting *et al*., 2017) and many sources indicate the loss of biodiversity at an exceptional rate (Millennium Ecosystem Assessment, 2005; Vamosi and Vamosi, 2008). The future of humanity depends on the goods and services from biodiversity such as food production, clean water, climate stability, medicinal plants, plant pollination, nutrient cycling, clean air, carbon sequestration, recreation and tourism, etc. (Millennium Ecosystem Assessment, 2005) provided by a well-functioning structure of biological diversity (Yessoufou and Davies, 2016). Unfortunately, this need might bring the loss of these ecosystem goods and services on a particular concern (Millennium Ecosystem Assessment, 2005). The risk of species extinction is linked in several ways to human population growth and activities including habitat destruction, invasive alien species and over-exploitation (Harberl *et al.,* 2007; Winter *et al.,* 2009; Willis *et al.,* 2010), as well as climate changes (Millennium Ecosystem Assessment, 2005). Dirzo and Raven (2003) asserted that the loss of biodiversity is the one irreversible global environmental aspect that can change the face of our earth today.

However, climate change, for instance, is predicted to be a main driver of extinction in the future of biodiversity, due to intervals in the ability of species to adjust their physiology and life histories (e.g. phenology, abundance, distribution and interaction, etc.) to match the new climate regime (Willis *et al.,* 2010; Cahill *et al.,* 2012). A study of the International Conservation projected that climate change could drive a quarter to one-half of world’s land (animals and plants included) to loss by the end of this century (IUCN, 2010; Foden *et al.,* 2013; Miller and Spoolman, 2017). However, at the international policy target of a 2^{o}C post-industrial rise, which experts now agree is no longer achievable, global extinction risks have increased from 2.8 to 5.2% at present (Fuss *et al.,* 2014). Nonetheless, if the earth warms to 3°C, the extinction risk will rise to 8.5% which means that climate change will threaten one in six species globally (16%) then it could distress ecosystems and the services they give to humans (Lawler *et al.,* 2009). A good example is coral reefs, which could be missing in the next century if global warming continues at the current tendency (Kannan and James, 2009). The signal of climate change-induced extinctions will become progressively more apparent if there is no action to limit future climate change (Urban, 2015).

In the period from 1950 to 2011, worldwide people increased from 2.5 billion to 7 billion (Visconti *et al*., 2015) and the expectation shows that human population will show an exponential growth to reach 9.8 billion by 2050 (United Nations, 2004). Indeed, current predictions put the possible number of people on the planet at 11 or 15 billion by 2100 (Gerland *et al.,* 2014). Consequently, that growth will exert pressure on natural resources and will continue to drive extinctions within a short period (Baillie *et al*. 2004; Pullaiah *et al.,* 2015). Potentially, it could decrease the provisioning of service deliveries (i.e. species and biodiversity particularly in the Tropics) (Vamosi & Vamosi, 2008; Archard *et al*., 2002; Wake and Vredenburg, 2008) at the time when demand is growing, as conflict between human development and wildlife still ongoing (Santini *et al.,* 2016). The elevated rates will be in tropical biomes particularly, which are known for their unique life-form diversity (Vamosi and Vamosi, 2008). However, there is an expectation that the future rate of species extinction could be raised by at least a further order of greatness over the next few hundred years (Tafirei, 2016). Nevertheless, that extinction rate differs from one species to another, which makes a pattern referred to as non-random extinction (Yessoufou and Davies, 2016). Pullaiah *et al.* (2015) demonstrated that the world could lose more than a million species of plants and animals during the next 20 to 30 years, principally because of environmental changes due to human activities. These activities continue to be the main risk to species diversity and long-term survival (Volis, 2016). Consequently, it is a matter of urgency to understand how the ongoing extinction crisis will affect the provisioning of critical ecosystem services (Yessoufou and Davies, 2016).

In their recent work, Miller and Spoolman (2017) demonstrated that the past five mass extinctions have been caused by abiotic factors like asteroid airstrikes and volcanic eruptions in natural climate shifts. For now, scientists are now in agreement that we are in the sixth mass extinction period of human history (Magurran and Dornelas, 2010; Barnosky *et al*., 2011; McLellan *et al.,* 2014). Humans (Anthropogenic period) are now causing this current sixth mass extinction through the co-option of resources, the spread of pathogens, the destruction of habitats, the introduction of non-native species and changing global climate (Barnosky*,* 2009; Vredenburg *et al.,* 2010). Pievani (2014) confirmed that we are not yet exactly in the middle of the sixth mass extinction, but then the rate is higher than caused by abiotic factors. Cafaro (2015) summarized three possible ways to think about the sixth mass extinction, such as i) the loss of important resources (as error), ii) interspecies genocide (as crime), and ii) the evidence that humanity is cancer on the biosphere (as inevitability). He then mentioned that this mass extinction of Earth's biodiversity is irresponsible and representing a serious mistake, that humanity will come to regret.

However, the recent rate of species loss might be 1,000 to 10,000 times greater than observed in the past extinction (Millennium Ecosystem Assessment, 2005; Pullaiah *et al.,* 2015) and most species on Earth would be eliminated within 100 years at this current rate of loss (Miller and Spoolman, 2017). The International Union for the Conservation of Nature (IUCN) in 2010 reported that amphibian species are the most at risk among vertebrates with an average of 41% to be threatened, and that estimation showed how much this species is facing an uncertain future. Nevertheless, 21% of fish are threatened with 20% of continental mammals, nearly 12% of the world’s bird species and 10 % of temperate regions’ plants have already been lost (IUCN, 2010; Pullaiah *et al.,* 2015). Also, at the islands of tropical Oceania, up to 1800 bird species were estimated to have become extinct in the ~2000 years since human colonization (Ceballos *et al*., 2015). Kannan and James (2009) mentioned that destruction of habitat has played an important role in extinctions, particularly those related to Tropical Forest. Some factors that contribute to biodiversity's habitat destruction are over-consumption, over-population, land-use change, deforestation, pollution (air pollution, water pollution, soil contamination) as well as climate change.

As over 70% of flowering plants assessed globally are at risk of extinction (IUCN, 2010), suggesting that this proportion is much higher than the one reported to vertebrates (22%) and the risk of extinction is more worrisome. Conversely, existing knowledge indicates that biological or ecological factors and evolutionary history pre-dispose many taxonomic groups to the extinction risk (Davies *et al.* 2011; Yessoufou *et al.,* 2012). A better explanation is that traits history of existence like body size predispose vertebrates to the risk of extinction (Cardillo, 2003; Yessoufou and Davies, 2016) but for plant species, extinction risk is linked to their existing history than their evolutionary (Vamosi and Wilson, 2008; Daru *et al*., 2013). Besides, the evolutionary history of a species may be more important than its life history in the explanation of extinction risk (Yessoufou and Davies, 2016).

1.3 Current conservation strategies on cycad species

To conserve biodiversity at global scale in the facade of the ongoing extinction crisis is one of the ideal remedies that would preserve the whole diversity and continue to provide ecosystem services to humanity (Millennium Ecosystem Assessment, 2005). However, those plans are conceptualized to take on public policy and concerns affecting societies, ecosystems, cultures, etc. at the global and national scale (Gascon *et al.,* 2007). Nonetheless, restricted-range for endemic species, one of the major approaches in IUCN threat categorization, are given priority on a global scale (Myers *et al.,* 2000; Olson *et al.,* 2001). So, this unique conservation on a global scale for endemic species correlates poorly with species richness and species threat levels (Orme *et al.,* 2005), and could lead us to miss the right goal (Isaac *et al.*, 2007). Indeed, the efforts of conservation planners are focused on species or habitats that need the most urgent attention (Isaac *et al.*, 2012), even if globally we do have enough resources.

Much literature has been written in the support of cycad conservation strategy at a global scale (Osborne, 1990; Donaldson, 2003; 2008; Daly *et al.,* 2006). However, with the numerous features compromising cycads over the past two decades, and the idea of cycad life history, it looks like future generations could not be able to watch these "living fossils" inside their natural habitat if efforts are not made now (Retief, 2013). Goël and Khuraijam (2015) have explained that most of the cycads occur on the top of endangered plants, and their future does not look very bright. One of the activity plans established by the International Union for the Conservation of Nature (IUCN) Cycad Specialist Group (CSG) is to multiply cycads artificially and utilizing seeds collected from the wild, to help the restoration of wild populations (Donaldson, 2003). In many countries, the conservation portfolio includes natural protected areas (NPA), community-based conservation (CBC), and *ex situ* conservation (Luo *et al*., 2014; Vovides *et al.,* 2010). Cycad species have the status of being threatened, so there is an urgent need to understand the rate at which populations are declining and to determine the factors that accelerate these declines (Mankga and Yessoufou, 2017).

The question of where and why to apply which conservation strategies remain very important. However, local communities in Mexico, for instance, have set up successful projects by selling only cycad seeds, but the effectiveness of this plan is upset by trying to discover sufficient marketing systems and developing reliable trading partners to guarantee that selling of the plants for the project is self-sustaining (Donaldson, 2003). Donaldson (2003) initiated the idea that the need for formulation and implementation adequate conservation strategies for threatened species that are represented by unique and small populations on a narrow geographic range. Nevertheless, the Convention on International Trade in Endangered Species (CITES) Appendix I lists species that are threatened with extinction and prohibited from entering international trade except for non-commercial purpose (e.g. for scientific research), while Appendix II includes species that may become threatened with extinction if the trade is not regulated and the last Appendix III lists species that require watching. Therefore, these Appendices are periodically reviewed (Pullaiah *et al.,* 2015) and more studies are needed to be undertaken to improve global understanding of these developments (Marler and Marler, 2015).

The National Environmental Management Biodiversity Act (NEMBA) 2004, Section 57 (2) in its amendment made in May 2012 hoped to assist the achievement aims of Biodiversity Management Plans (BMP) through more stringent regulation of the cycad trade in South Africa (Retief, 2013). Removal and trade of any part of *Encephalartos* specimens in the wild, for example, that are listed as threatened or protected is banned in South Africa (DEAT, 2012). This means that any specimen of this genus, which is listed as critically endangered or endangered, may not be traded within South Africa or exported outside the country for the next five years, especially those having a stem diameter from 7 to 15 cm or until conservation targets are reached (DEAT, 2012). In South Africa, the BMP aims to execute this strategy on *E. latifrons*, a critically endangered (CR) cycad with fewer than 60 individuals left in the wild (Da Silva *et al.,* 2012). The main aim is to make safe and restore existing populations (DEAT, 2010). Nevertheless, the BMP allows landowners or communities to trade with propagated seedlings from wild cycads on condition that they have the right permits and a certain percentage of seedlings are used for restoration purposes (DEAT, 2010).

1.4 Applications of Evolutionary Distinctiveness

Evolutionary Distinctiveness (ED) explains the phylogenetic relatedness of a species with others on a phylogeny. In Figure 1 below, there is an explanation of how to calculate ED. It gives ED score of species A given by the sum of the ED scores for each of the branches between A, and the root of the phylogeny. Species A is linked to the root by only one branch that is 2 million years (MY) long, consequently, ED score for A is 2/1 = 2MY. However, species B is connected to the root by two branches of 1 MY each; the first branch is a terminal branch that subtends only one species (which is B) while the second one subtends two species (B and C). Therefore, ED score for B is 1/1+1/2 = 1.5 MY. Species C has the same ED score with species B and the explanation is because they are sister species. Species that have very few relatives will have a high ED value (e.g. species A) compared to those with several relatives (e.g. species B or C). IUCN gives the categorization of threat level for species risk assessment such as Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN) and Critically Endangered (CR) (IUCN, 2010).

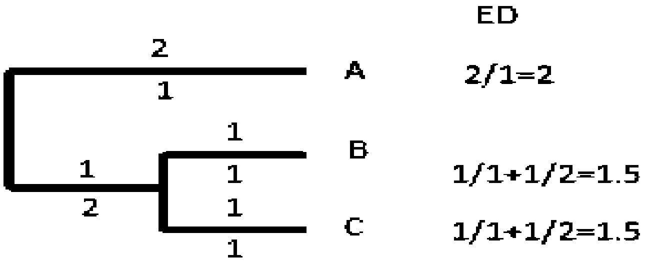

Figure 1: A theoretical phylogeny of three species A, B and C explaining how to calculate ED scores. Numbers above each branch indicate the length of the branch in million years before the present and numbers below show the number of descendent species (Tafirei, 2016).

1.5 Research problem

The ongoing six mass extinction events are characterized by the loss of two-thirds of biodiversity (Millennium Ecosystem Assessment, 2005). This loss raises a global concern, as humanity relies on the goods and services that biodiversity provides (e.g. foods, medicine, pollination, recreation, etc.). However, biodiversity on a global scale is increasingly under massive pressure, calling for renewed conservation efforts (Millennium Ecosystem Assessment, 2005). It is very difficult to conserve all species because existing measures for conserving biodiversity are facing global limitations (Lung *et al.,* 2014). Limited funds that might be allocated for conservation could be used in developing countries, for the simple reason that these areas are today seen as a home for the vast majority of biodiversity (Rolland *et al.,* 2014; Lung *et al.,* 2014). In South Africa, for instance, legislation on cycads is one of the strictest in the world (Donaldson, 2003), but poaching of cycads in an illegal manner is still common and high in number (IUCN, 2010; Cousins *et al*., 2012; Okubamichael, 2016). Because of all these limitations, the priority is to save threatened species that require the most urgent attention.

However, in animal species, for instance, the extinction risk was related to the mass of their body and generation time as well as the geographic range. Consequently, species with these three above mentioned characteristics would be the most at risk (Bennett and Owens 1997; Russell *et al.*, 1998; Purvis *et al.*, 2000; Cardillo, 2003; Fisher and Owens, 2004; Cooper *et al.,* 2008; IUCN, 2010). For this present study, maximum diameter and maximum height represent the body size (see also Sodhi *et al.*, 2008). It is essential to understand better what pre-disposes biodiversity to the extinction risk, to report to conservation decision-makers and forecast the future risk of the historical extinction actions. Although a huge body of literature devoted to this question was released, especially concerning the evolutionary basis of species loss and their drivers but most of them have shown inequality. In addition, the hard works of commitment to disentangle these drivers and the patterns of extinction risk have been focused on vertebrates (i.e. mammals: Isaac *et al.,* 2007; updated by Davies and Yessoufou, 2013; Luiz *et al.,* 2016, birds: Jetz *et al.,* 2014, reptiles: Isaac *et al.,* 2012; Veron *et al.,* 2016 as well as fish: Adeoba *et al.,* 2019).

Furthermore, the comparatively few studies on extinction risk for plants have made priorities to angiosperms (Sodhi *et al.,* 2008; Yessoufou *et al*., 2012; Leao *et al.,* 2014; Daru *et al*., 2015; Daru and le Roux, 2016) with no comparable efforts devoted to gymnosperms, even though the latter are more at risk of extinction than angiosperms (e.g. ~70% of cycads are at risk of extinction: Yessoufou *et al.,* 2017). As result, informations about vertebrates and angiosperms to be pre-disposed to extinction risk, also how their phylogenetic trees would be distressed by the damage of species are well known (Davies *et al.*, 2011; Mooers *et al.,* 2012; Davies and Yessoufou, 2013). This high risk of extinction for cycads is due to overexploitation, habitat destruction, species biology and ecology as well as climate (Mankga and Yessoufou, 2017). Cycad species could be lost in a near future if measures are not made now, simply because it has a very low dispersal ability, a very limited range of pollinator and a very restricted distribution range (IUCN, 2010). Many works showed that the result of this extinction is the risk of losing important evolutionary history from its tree of life (Davies and Yessoufou, 2014; Davies, 2015; Yessoufou and Davies, 2016), and this will finally contribute to the disruption of ecosystem functions and services and other biodiversity associated to cycads.

Therefore, regarding the inability to preserve all species simultaneously in an efficient manner, researchers can only prioritize and focus their efforts of conservation on species that represent unique evolutionary history. However, to achieve this, there is an increasing evidence that focuses on ED, as a single diversity metric (Jetz *et al.,* 2014; Redding *et al.,* 2014, 2015) or in combination with threat using (Isaac *et al.,* 2012) would likely lead to safeguarding the most evolutionary in a particular lineage. As such, there is an urgent need to understand how best this plant group (cycads) and their evolutionary diversity can be safeguarded in the circumstance of the ongoing destruction crisis at the Tropics. To reach this global objective, a recent study demonstrated, again using vertebrates as a case study, with an integrative approach, which combines biogeography, evolutionary data and extinction risk information (Jetz *et al*., 2014). This study is the one best suited to elucidate how conservation decisions can be designed efficiently to prevent biodiversity loss. Such an opportunity for an integrated analysis of the extinction risk for cycads is missing, precluding us from designing a bigger picture of globally conservation plan for cycads. The present project aims to fill this knowledge gap.

1.6 Rationale for the study

The rationale for this project is that cycads are the most threatened group of plants (IUCN, 2010; Yessoufou *et al.,* 2017), but we still have a poor knowledge of what pre-disposes these species to such a high risk of extinction. Also, how evolutionary and extinction risk data can be analyzed within a biogeographic framework to inform conservation decisions on a global and national scale. In general, the future of humanity relies strongly on the continued delivery of ecosystem services (food, medicinal plants, pollination, clean air, erosion control, etc.) by the environment (Millennium Ecosystem Assessment, 2005). Unfortunately, and perhaps unsurprisingly, human activities are driving the loss of service deliveries (i.e. species and biodiversity) at an unprecedented rate, particularly in the Tropics (Vamosi and Vamosi, 2008). Therefore, scientists are now convinced that we are in the sixth mass extinction period on human record (Barnosky *et al.,* 2011).

Indeed, direct or indirect anthropogenic forces mostly drive species extinction (e.g. unsustainable use of resources, invasion of alien species, climate change, etc.; Millennium Ecosystem Assessment, 2005). Species loss is shown to be the end-result of a long procedure of roughly three stages, which define the temporal and spatial dynamics of biodiversity. This end-result is as follows: i) species radiation and accumulation over time (temporal dynamic), ii) species dispersal to occupy ecologically suitable niches (a spatial dynamic that defines their biogeography) and perform environmental functions (including various ecosystem services), and iii) their extinction (Mankga and Yessoufou, 2017). These three stages are linked in such a way that, for example, the radiation history of plant species can pre-disposes them to extinction (Davies *et al*., 2011). However, a better understanding of the dynamic and functioning process of biodiversity is necessary, to guide actions towards environmental management and conservation that ensures a sustainable delivery of ecosystem services, as targeted in the NEMBA (Act 10).

Thus, Structural Equation Modeling (SEM) for this study was used to give the significance of path analysis once trying to elucidate the patterns that are causing the cycad extinction crisis. However, studies that explicitly address SEM applications in ecology and environmental sciences are limited (Grace and Pugesek, 1997: 1998; Shipley, 2000). Some of them were focused on wetland management (La Peyre *et al*., 2001), aquatic ecosystems (Malaeb *et al*., 2000; Xiao-fu *et al.,* 2016), groundwater quality (Belkhiri & Narany, 2015), the relative effects of abiotic conditions (e.g. soil salinity, elevation, nutrient content), disturbances (e.g. herbivores) and biomass density on plant species richness (Grace and Pugesek, 1998). Consequently, no SEM model was ever used for cycad species, which is a gymnosperm plant. Recent work of Mankga and Yessoufou (2017) that is taken as a case study, used the phylogenetic relative method and the growing link mixed-effect model to determine and explain some factors that drive cycad diversity on a global scale, but no SEM model was even mentioned. This work is the first-ever to address and integrate the extinction risk of cycad species by using the SEM model.

1.7 Aim and Objective of the study

Given that cycads are the most threatened group of plants, the main aim of this study is to inform conservation decision-makers to be aware of the factors that drive the extinction risk of cycad species.

The specific objective is:

- **Objective**: To formulate and test a meta-model that explains the patterns of the extinction risk of cycads.

1.8 Formulation of hypothesis

The theoretical model (SEM: Figure 2 below) was designed by predicting how a variable (response) could either be positively (direct path) or negatively (indirect path) affected by another variable (predictor) and vice-versa. The theoretical model was built based on the following assumptions: we assume that ED would have a positive relationship with maximum height, IUCN threat status and number of threats, but a negative relationship with generation time. The expectation that species with high-ED level would be threatened means that they would be exposed to extinction risk (Yessoufou *et al*., 2017; Adeoba *et al.,* 2019). Maximum altitude would have positive relationship with two other variables: number of threat (defined as the diversity of threats) and generation time; but negative correlation with two variables as well: geographic range (defined as surface area of geographic ranges in km^2) and IUCN threat status. The expectation that species found in elevated altitude might have a chance to survive longer generation time, simply because these areas are, consider as 'safe haven for threatened species' (Fjeldsã and Lovett, 1997; Fjeldsã *et al*., 2012). Alternatively, species that are found in lower altitude might have a considerable number of threats because they would be easily spotted by illegal poaching (e.g. over-collection, deforestation, medicine usage, etc.; Voeks, 2004; de Albuquerque, 2006) and invasive species as well as exposed to other environmental extinction drivers (i.e. flood and drought; Mankga and Yessoufou, 2017). Number of threat would have a positive relationship with IUCN threat status and height, but negative correlation with generation time. Range (km^2) would have positive relationships with IUCN threat status, maximum height and maximum diameter. The expectation that species found in protected areas would be less threatened, because they are less in contact with illegal collectors (Gülez, 1992), and they might invest in height as well as diameter and would have chance to survive longer. Likewise, maximum diameter would have a negative relationship with maximum height and IUCN threat status, and the expectation that a species with vast diameter will not invest in height and will be the target for poaching especially for medicinal purposes (Voeks, 2004; de Albuquerque, 2006) and fire as well. Maximum height would have a positive relationship with IUCN threat status but negative with generation time. Finally, generation time would have a positive relationship with IUCN threat status.

Then, the theoretical meta-model (SEM: figure 2 below) was built to translate all these expectations for the hypothesis. Nonetherless, eight variables used for this study are well presented as well as their predictions (Figure 2).

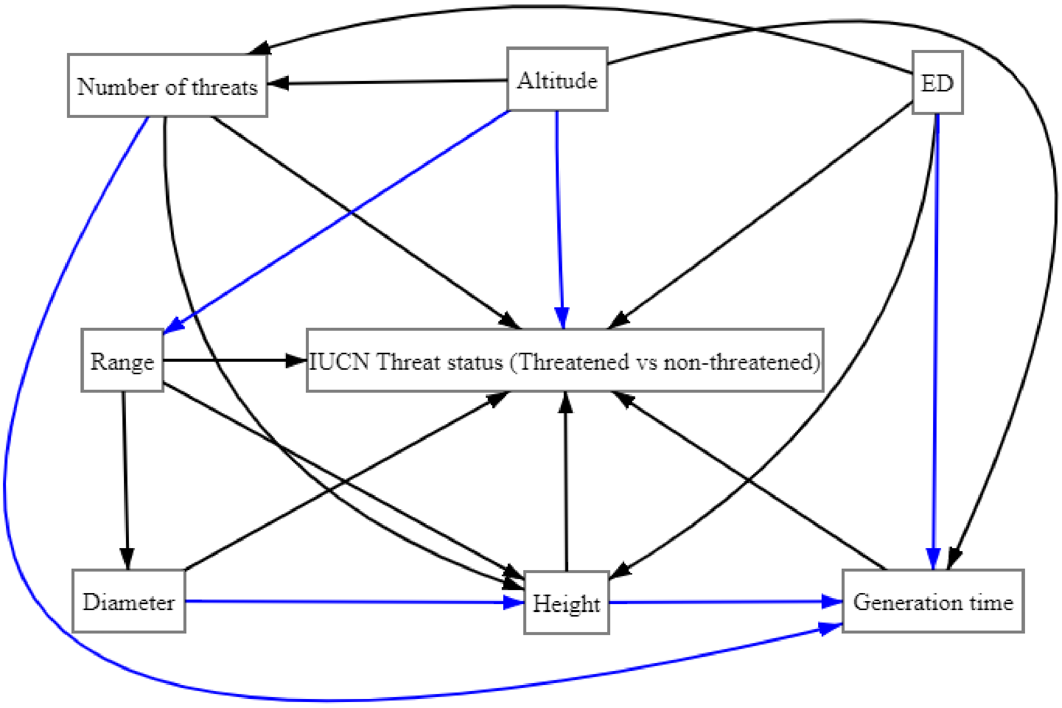

Figure 2: A theorethical Meta-model (SEM) illustrating the prediction of hypothesis.

Different paths (arrows) represent unidirectional relationships between variables (predictors towards responses) and are colour-coded: black arrows (direct path) denote the positive relationships between two variables and blue arrows (indirect path) denote the negative relationships between two variables. In conclusion, this theoretical metal-model will be tested in the empirical study following the data analysis process.

1.9 Dissertation outline

The present dissertation is structured in six chapters, including an Introduction and a Conclusion. The Introduction (Chapter one) defines the general scope of the study (providing the background, research problem, rationale, aim and objectives). Chapter two is focused on the Literature review, while Chapter three provides the Methodology. Presentation and analysis of data are carried out in Chapter four, which gives the results of the study. Chapter five discusses the results of the thesis. The final Chapter six highlights the conclusion of the study by making some recommendations to identify the probable areas for researches to come.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Cycads are a group of plants known as gymnosperms (plants which bear naked seeds) of picky attention due to their evolutionary history (Nagalingum *et al*., 2011; Yessoufou *et al.,* 2014; Condamine *et al.,* 2015). They belong to an ancient order of Cycadales (Giddy, 1974; Nostog and Nicholls, 1997) and a separate class Cycadophyta (Hill, 1999). The order Cycadales is considered as a very prehistoric group of plants going back about 300 Mya (million years ago) in the Palaeozoic era (Hendricks, 1987; Pot *et al.,* 2010; Donaldson *et al.,* 2003; Nagalingum *et al.,* 2011; Taylor *et al.,* 2012; Zonneveld and Lindström, 2016). In overall appearance, cycads, which are a small group of gymnosperms (non-flowering seed plants), resemble palms by their thick columnar and are long-living perennial evergreen plants (Taylor *et al.,* 2012). They also resemble large ferns and share morphological characteristics of angiosperms (Norstog and Nicholls, 1997; Brenner *et al.,* 2003; Hill *et al.,* 2004), but they differ significantly in reproduction and detailed structure (Salas-Leiva *et al.,* 2013).

They are distributed in the neo-tropics, with a high predisposition to tropical and subtropical regions where temperatures and humidity are high (Donaldson *et al.,* 2003; Da Silva *et al.,* 2011; Taylor *et al.,* 2012). Due to their ability to preserve ancestral characteristics like flagellated sperm, cycad species are the most ancient group amongst the contemporary spermatophytes still living today (Vessey *et al.,* 2004; Salas-Leiva *et al.,* 2013). Zheng *et al.* (2017) believed that they are the oldest and most ancient assemblages of worldwide living seed plants and they have been around since the time of the dinosaurs. Cycads are also indispensable to understand the origin and subsequent evolution of seed plants and are taxa that bridge the major evolutionary transition in plants (Zheng *et al.,* 2017). They approximately covered 20% of the world's flora during the Jurassic-Cretaceous period, when the Dinosaurs roamed the Earth, and for this clade, the proportion of the threatened species remains high (> 80%) (See also Donaldson, 2003; Taylor *et al.,* 2009; IUCN, 2010). Salas-Leiva *et al.* (2013) estimated that cycad species diversification had taken place in the Eocene and Oligocene periods. They had particularly been distributed worldwide in the Mesozoic era (Hermsen *et al*., 2009), but Nagalingum *et al* (2011) confirmed that the extant cycads deviate around 12 to 2 Mya. However, Mesozoic is an era characterized by an increased rate and diversity of fossil cycads (these plants proliferated during that period), broadly distributed throughout the comparatively uniform climate of the supercontinent Pangaea (Taylor *et al.,* 2009). Hermsen *et al.* (2009) believed in particular that the well-known historical record of cycads is in the Triassic epoch, not only because of the marked increase of cycad taxa definition in terms of number but also because some of the most well preserved and informative taxa are from this period.

Cycads have been recognized as gymnosperm plants since their first description by Linnaeus in his "*Species Plantarum"* in 1753 of seed-bearing plants, and are a distinct, phylogenetically isolated group (Doyle and Donoghue, 2012; Ran *et al.,* 2010). Nonetheless, previous studies have grouped them with Conifers, Gnetophytes and Ginkgo (Norstog and Nicholls, 1997). Thus, current studies based on molecular and morphological data indicate that cycads are monophyletic (Hill *et al*., 2003; Rai *et al*., 2003; Bogler and Francisco-Ortega, 2004; Vessey *et al.,* 2004; Chaw *et al*., 2005; Zgurski *et al.,* 2008; Crisp and Cook, 2011; Nagalingum *et al.,* 2011; Condamine *et al*., 2015). This means they demonstrate a single evolutionary origin (Donaldson *et al.,* 2003). They have rosettes of multiple leaves with pinules and a height of approximately from 0.2 to 20 metres (Donaldson *et al*., 2003; Vessey *et al.,* 2004). They are dioecious (i.e. male and female cones are placed on separate plants), which is a characteristic of a true gymnosperm (Hill *et al.,* 2004; Taylor *et al*., 2012; Salas-Leiva *et al.,* 2013). Their reproductive organs are produced in cones and are known as the most primitive living seeds (Chamberlain, 1925).

Cycad species are well equipped against environmental threats (fires and drought) with the ability to biosynthesize a variety of protective and secondary compounds such as glycosides and non-protein amino acids (Brenner *et al.* 2003; Okubamichael *et al.,* 2016). Donaldson *et al.* (2003) and Taylor *et al.* (2012) linked the survival to individual longevity in cycads and their ability to produce toxic substances, which deter herbivores. However, another probable explanation for the long-term survival of these taxa for many centuries is because they grow extremely slowly and are remarkably resistant to pathogens and predators (Giddy, 1974; Raimondo and Donaldson, 2003). The Southern African clades are estimated to survive through the development of key innovations (e.g. underground stems) and their subterranean stem (Hill *et al.,* 2004) could have enabled them to adapt to high temperatures and the aridity of the transition of the Pliocene-Pleistocene era in that region (Yessoufou *et al.,* 2014).

Evidence suggests that naturalists and botanists of Europe discovered cycads in the 1700s-1800s and, since their discovery, these plants have been subject to the significant fascination of botanical and horticultural interest around the world. As a result, an enormous quantity of cycads has been collected from the wild to private property and botanical gardens (Pearson, 1905; Giddy, 1984; Donaldson, 2003). In addition, in the mid-1990s, there has been an increasing awareness in cycad ethnobotany in places like Central America (Bonta, 2010), India (Radha and Singh, 2008; Krishnamurthy *et al*., 2013) and South Africa (Osborne *et al*., 1994; Ravele and Makhado, 2009; Cousins *et al.*, 2012; Bamigboye *et al*., 2017). A better understanding of this group of plants could then provide evolutionary insights into the trends of seed plants (Zheng *et al.,* 2004; Wang *et al,* 2007). This could help in the determination of connections between their origins and present-day counterparts before losing them, as they are under a tremendous risk of extinction (Da Silva *et al.,* 2011).

2.2 Cycads biogeography

The living cycad is divided into three families, namely: Cycadaceae, Stangeriaceae and Zamiaceae (Chamberlain, 1925; Osborne *et al.,* 2012), with 11 genera such as *Bowenia, Ceratozamia, Chigua, Cycas, Dioon, Encephalartos, Lepidozamia, Macrozamia*, *Microcycas, Stangeria* and *Zamia* (Donaldson, 2003; Donaldson *et al.,* 2003; Osborne *et al.,* 2012; Condamine *et al.,* 2015; Yessoufou *et al*., 2017). They are only limited to Tropical and Subtropical regions of Africa, Asia, Australia, Central and Southern America, with a few of them found in the oceanic islands (Nagalingum *et al.,* 2011; Osborne *et al.,* 2012; Taylor *et al.,* 2012; Salas-Leiva *et al*., 2013).

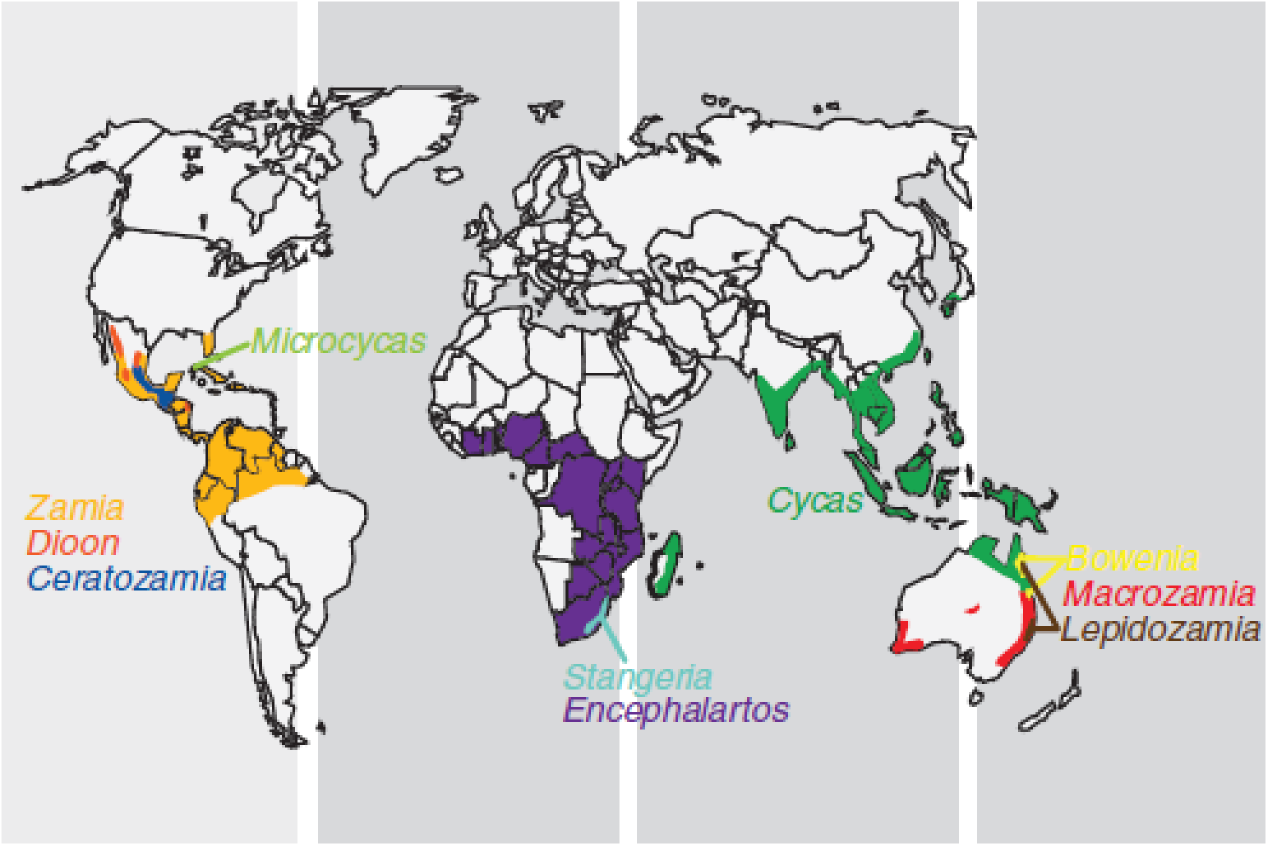

Figure 3: Global distribution range map of the Cycad genera (Nagalingum et *al.,* 2011).

Generally, most cycad species occur in small populations in remote pristine vegetation (Donaldson, 2003; Osborne *et al.,* 2012; Taylor *et al.,* 2012) and they have a highly structured distribution of an isolation pattern in distance even at small geographic distances (Cibrian-Jaramillo *et al.,* 2010). However, the study of Donaldson *et al.* (2003) indicated that these small relict populations might have once been more widespread, even though Hamrick (2004) argued that small and restricted populations might not necessarily result in extinction. Yet, it could have an impact on general cycad diversity (Da Silva *et al.,* 2011), and it appeared to have pre-disposed them to a high risk of extinction (Salas-Leiva., 2013). Several genera existed in the past but do not have any of their current living, due to the great extinctions within the cycad group, that have contributed perhaps to the irregular distribution of extant cycads that we observe today (Donaldson *et al.,* 2003; Taylor *et al.,* 2012; Salas-Leiva., 2013).

2.3 Cycad diversity and changes in taxonomy

The "World List" of cycads has been changed at several times, owing to the elevated morphological resemblances amongst species, which result in the discoveries and a very long list of synonyms (Hill *et al.,* 2004; Osborne *et al.,* 2012), causing multiple readjustments in their taxonomy. Osborne and Hendricks (1985) published the first world list of cycads. Thereafter, various other lists were presented such as Stevenson and Osborne (1993a, b) and Stevenson *et al.* (1995). However, Stevenson *et al.'s* list provided a list of synonyms for each genus to have 352 species in total. All of these lists improved the understanding of these species and led to increase their numbers recognized at global scale.

2.3.1 Family Cycadaceae

Currently, the Cycadaceae has only one genus *Cycas* and their members are distributed in South China (where they originated from) and Indochina in the Miocene (Xiao and Möller, 2015). They then occur in Northern Australia and along the West African coast, Madagascar, India, Japan, and a great number of oceanic islands of the Pacific (Donaldson, 2003; Donaldson *et al.,* 2003; Da Silva *et al.,* 2011; Cousins and Witkowski, 2017). However, this family is viewed as an early offshoot from the rest of the cycads (Tafirei, 2016). *Cycas* has the widest distribution range with almost 110 species, from the Eastern Africa eastwards to the Pacific islands and from China and Southern Japan southwards to Australia (Hill, 2004; Figure 3). Its widespread dispersal is a result of long-distance transoceanic dispersal events (which made possible for the progress of a key improvement like spongy endocarp) (de Laubenfels and Adema, 1998; Xiao and Möller, 2015). Dioecious palm-like shrubs with aerial subterranean and cylindrical stems, as well as loosely arranged megasporophylls characterized this genus (Hill *et al*., 2004; Osborne *et al.,* 2012). Nonetheless, they form a basal group (Vessey *et al.,* 2004) and are commonly understorey shrubs, but can sometimes be quite large if soils are drained or if they occur in the savannah.

African continent hosts' only one species (emblematic *Cycas thouarsii*) amongst *Cycas* genera (Cousins and Witkowski, 2017) and remaining species occur in Australasia (Donaldson, 2003; Nagalingum *et al.,* 2011; Calonje *et al.,* 2016). Evidence suggests that this species firstly occurred exclusively on Madagascar then humans have brought into the African continent during the heyday of mercantile activities in the western Indian Ocean. Then after, it yields seeds that float in water and ocean currents could probably have carried these seeds to the African coast (Goode, 1989).

2.3.2 Family Stangeriaceae

The family Stangeriaceae seems to have originated in the very old supercontinent of Gondwana (Donaldson, 2003) and it is the cycad family having the smallest number of species (Hill *et al.,* 2004). Its fossil was also found in Lower Cretaceous stores (70–135 Mya) in Argentina (Artabe and Stevenson 1999; Donaldson *et al.,* 2003). This family comprises two genera, namely: *Bowenia* and *Stangeria* (Donaldson *et al.,* 2003; Osborne *et al.,* 2012; Taylor *et al.,* 2012; Condamine *et al.,* 2015). However, *Bowenia* is endemic to Australia with two species: *Bowenia serrulata* and *B. spectabilis* (Donaldson *et al.,* 2003). These two species are dioecious fern-like shrubs like every cycad species, with a naked subterranean stem capable of producing one or many shoots (Hill, 2004) with leaves bi-pinnate and leaflets which do not bear a mid-rib.

The genus *Stangeria* has only one species (*Stangeria eriopus*) that is endemic to South Africa (i.e. the Eastern Cape and KwaZulu-Natal Provinces) and Southern Mozambique (Jones, 1993; Jones, 2002; Whitelock, 2002; Donaldson, 2003; Donaldson *et al.,* 2003; Osborne *et al.,* 2012; Salas-Leiva *et al.,* 2013; Cousins and Witkowski, 2017). It is also dioecious and fern-like and most of their members occur mostly in the coastal grasslands and inland forests alongside the eastern coast of South Africa (Vessey *et al.,* 2004). The plants' body consists of a big tuberous root that is carrot-shaped, with a subterranean branched stem (Osborne *et al.,* 2012). The stem may sometimes branch into 10 to 12 heads and each head may produce a cone at the same time (Giddy, 1974). Male and female cones are silvery pubescent at first when becoming brownish upon maturity and look completely different. Female cones are much bigger than male, but both have overlapping cone scales (Giddy, 1974). *Stangeria*, which has remained taxonomically stable (Donaldson *et al.* 2003; Hill *et al.,* 2007), is characterized by pinnate leaves and leaflets that have a mid-rib and lateral veins.

2.3.3 Family Zamiaceae

The Zamiaceae is the largest and the most widespread family of cycad, consisting of eight genera. Five of them are found in the Americas (e.g. *Ceratozamia, Chigua, Dioon, Microcycas* and *Zamia*), two in Australia (*Lepidozamia* and *Macrozamia*) and one in Africa (*Encephalartos*) (Jones, 1993; Whitelock, 2002; Donaldson, 2003; Nangalingum *et al.,* 2011; Salas-Leiva *et al.,* 2013). Zamiaceae is a more diverse family in terms of its geographical distribution, simply because it is not confined to one continent. This family is suggest to be present before the break-up of the super continent Pangaea (Donaldson, 2003). Africa is the only continent where all these three cycad families (Cycadaceae, Stangeriaceae and Zamiaceae) are found (Donaldson, 2003; Nagalingum *et al*., 2011; Yessoufou *et al.,* 2017) and South Africa is the only country on the African continent to harbors 38 cycad taxa found naturally. That makes this country to stand out as one of the greatest global hotspots for cycad diversity (Donaldson, 2008).

The genus *Ceratozamia* consists of 27 species (Osborne *et al.,* 2012) and most species belonging to this genus are endemic to the mountainous areas of Mexico, Guatemala and Honduras (Haynes, 2011). Haynes (2011) argued that *Ceratozamia* is well known for its sporophylls with protuberant paired horns, as well as its pinnate compound leaves. Thus, these leaves are straight and spirally arranged. Leaflets lack a mid-rib, but have parallel side veins and are articulate at the base (Hill *et al.,* 2004).

Dioon is a genus found naturally to Mexico and Central America and comprises 14 documented species (Osborne *et al.,* 2012). Some of their habitats are tropical forests, pine oak forests, dry hillsides, canyons, and coastal dunes. Members consist of grey or blue-green pinnate leaves, with non-articulated leaflets lacking a mid-rib, and Megasporophylls are broadly flattened, upturned and overlapping. Therefore, the unique feature of this genus that makes them different from any other cycads is the fact that *Dioon* has the presence of female cones, with two seeds attached to each sporophyll (Nostog and Nichols, 1997).

The genus *Encephalartos* comprises 65 species (Hill *et al*., 2004; Osborne *et al.,* 2012; Yessoufou *et al*., 2017) which inhabit humid tropical and subtropical regions of Africa (Vessey *et al.,* 2004; Osborne *et al.,* 2012) and members of this genus are unequally dispersed across African regions. For example, *Encephalartos barteri* is the only species that occurs in West Africa, while over 50% of the *Encephalartos* species are endemic to Southern Africa (The geographical region considered as the Centre of diversity for this genus) (Donaldson, 2003; Golding and Hurter, 2003; Yessoufou *et al.,* 2014). However, *Encephalartos* is distributed throughout 16 African countries from West to Central, as well as in East and Southern Africa. They similarly occur on the Indian Ocean Islands of Madagascar, Comoros, Seychelles and Zanzibar (Donaldson, 2003; Anderson *et al.,* 2007; Cousins *et al.*, 2012). In conclusion, South Africa is the only country on the continent, which harbors 37 *Encephalartos* species (Donaldson, 2008).

Nonetheless, there are no substantial changes noted in the genus *Encephalartos,* even though many changes were made to the cycad taxonomic group and this genus is considered as the better known of the cycad genera (Donaldson *et al.,* 2003). Members of *Encephalartos* have pinnate leaves and contain leaflets that lack a mid-rib as well as articulation (Hill *et al.,* 2004). The history of this genus started with the separation of its sister's taxa *Encephalartos* (Africa) and *Lepidozamia* (Australia) and could be correlated to the separation of Africa and Australia approximately 80 Mya (Hill *et al*., 2003). They appear to have perhaps evolved from a similar ancestor in Gondwana (200-135 Mya), before Australia and Africa split (Bogler and Francisco-Ortega, 2004). In their group study, Hermsen *et al.* (2006), found by using least age mapping techniques, that *Encephalartos* appears to have split at approximately 33 Mya from the *Lepidozamia-Macrozamia* lineage and not later than the Eocene period.

The genus *Lepidozamia* consists of two species (*Lepidozamia hopei* and *L. peroffskyana*) (Osborne *et al.,* 2012) and both of them are endemic to eastern Australia. They are closely related to the large southern cycad genera *Macrozamia* from Australia and *Encephalartos* from Africa (Donaldson *et al.* 2003; Hill *et al.,* 2004). The unique cuticular characteristic of *Lepidozamia* is the orientation of epidermal cells in the leaves of this genus, which is relative to the axis of the pinna that is unlike other genera (Hill *et al.,* 2004; Condamine *et al.,* 2015).

Macrozamia is a genus in Zamiaceae with 41 documented species (Osborne *et al.,* 2012). Hill *et al.* (2004) argued that over 80% of these species are found in Eastern Australia and the rest in the central and southwest areas of the continent and they are dioecious like all cycads. For other genera, leaves erupt all at once, unfortunately, for this genus; members are unique and produce their new leaves one at a time (Hill *et al.,* 2004). However, most of *Macrozamia* produce subterranean palm-like trunks up to 20 feet tall or more and have flat and thin leaflets that taper at the end (Chaw *et al.,* 2005).

Microcycas calocoma is the only one species described in the genus *Microcycas* and is endemic to Cuba (Donaldson *et al.* 2003; Hill *et al.,* 2004; Osborne *et al.,* 2012). Members are dioecious palm-like shrubs with tall aerial stems that bear numerous leaves, with their microsporophylls and megasporophylls being spiral (Hill *et al.,* 2004). *Microcycas* and *Zamia* are closely related (Bogler and Fransisco-Ortega, 2004).

The genus *Zamia* comes second to *Cycas* in term of distribution range and diversity (Taylor *et al.,* 2012) and consists of 75 described species (Osborne *et al.,* 2012; Yessoufou *et al.,* 2017). It is the only cycad genus of America, which can be found in both side of the Equator (Whitelock, 2002; Mooers *et al.,* 2012). *Zamia* is a genus endemic to Isthmus of Panama and this endemism is due to the highest cycad representation per unit land mass than any other region in the neo-tropics. This is the real reason that makes the Isthmus of Panama a cycad biodiversity hotspot (Taylor *et al.,* 2012), having 17 species where 12 of them are endemics to Panama. The Isthmus occurs in the tropics of the western hemisphere (Donaldson *et al.* 2003; Taylor *et al.,* 2012).

The figure below presents a photographic description of the diversity of cycad cones, as published in Calonje *et al.* (2011).

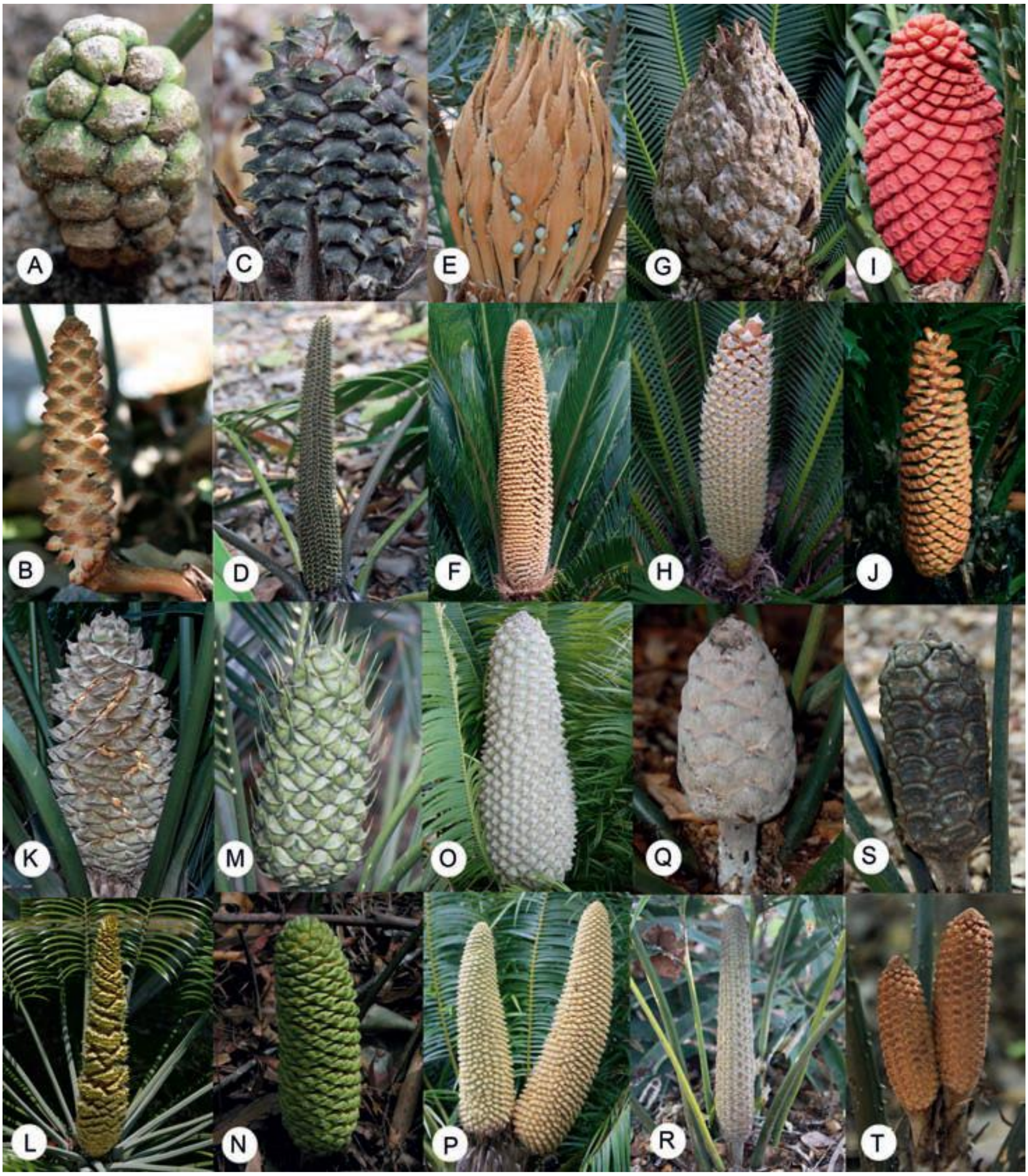

Figure 4: Seed and pollen cones for all cycad genera.

A) *Bowenia serrulata* seed cone B) *Bowenia spectabilis* pollen cone C) *Ceratozamia decumbes* seed cone D) *Ceratozamia decumbes* pollen cone E) *Cycas couttsiana* seed cone F) *Cycas revoluta* pollen cone G) *Dioon angustifolum* seed cone H) *Dioon angustifolum* pollen cone I) *Encephalartos ferox* seed cone J) *Encephalartos ferox* pollen cone K) *Lepidozamia hopei seed* cone L) *Lepidozamia peroffskyana pollen* cone M) *Macrozamia lucida seed* cone N) *Macrozamia lucida* pollen cone O)

Microcycas calocoma seed cone P) *Microcycas calocoma pollen* cone Q) *Stangeria eriopus* seed cone R) *Stangeria eriopus pollen* cone *S*) *Zamia imperialis* seed cone T) *Zamia imperialis* pollen cone.

Photos: All Michael Calonje except K: Larry Krauss and N: Irene Terry (Calonje *et al*., 2011).

CHAPTER 3

METHODOLOGY

3.1 Data collection

Data used in this present study were collected and retrieved from the work of Yessoufou *et al*. (2017), on which a total list of 339 taxa of global cycads was made. They compiled these taxa by following methodical writing searches like Lindström (2009), Nagalingum *et al*. (2011) and Osborne *et al*. (2012). However, Osborne *et al*. (2012) summarized the existing knowledge of cycad species based on their morphology, ecology and taxonomic discrimination to distinguish 331 cycad species. Nonetheless, Nagalingum *et al*. (2011) used DNA data to assemble a comprehensive phylogeny of global cycads that contains 199 species. Yessoufou *et al* (2017) assembled the list of these taxa (above mentioned), by combining Nagalingum *et al*.'s list (which used DNA-based phylogeny) with Osborne *et al*.'s list (used as the reference list). They (Yessoufou *et al*., 2017) also compiled IUCN threat categories for all taxa (http://www.redlist.org/, August 2018; Osborne *et al*., 2012): Data Deficient (DD: five taxa), Least Concern (LC: 47 taxa), Near Threatened (NT: 68 taxa), Vulnerable (VU: 78 taxa), Endangered (EN: 70 taxa) and Critically Endangered (CR: 67 taxa).

This present study complemented these data with some additional information on different threats to cycads available from various sources such as the IUCN database (http://www.redlist.org/, August 2018), as well as the current online World List of Cycads made by Calonje *et al*. (2017). This complement gave four additional species IUCN-considered as Extinct in the Wild (EW), which were not mentioned in Osborne *et al*.'s list. Therefore, all these 339 species of Yessoufou *et al*.'s list that is used as material for this present study are presented in Appendix I with their global distribution (location) as well as their threat status respectively.

3.2 Research methods

3.2.1 Probable predictors of the IUCN threat status

A list of recognized variables was assembled to fit the predictive models (i.e. SEM) of IUCN status for all global cycads. These variables included maximum altitude, maximum diameter, diversity of threats (also known as the threats number), geographic range (km^2), ED, generation time and maximum height, as well as threat status (threatened vs. non-threatened; see also Mankga and Yessoufou, 2017). However, seven variables [maximum altitude, maximum diameter, diversity of threats, geographic range (km^2), ED, generation time and maximum height] were considered as dependents variables to IUCN threat status which is the sole response variable in the model. Thereafter, the SEM model showed also how in some cases these predictors could look as response variables and vice-versa.

The diversity of threats (number of threat categories) was documented for every species. ED is a metric that approximates to the formative time of each species, such a species with a higher ED value is subtended on a phylogeny by a longer branch (Isaac *et al.,* 2007). In addition, ED values for each cycad species was collected from Yessoufou *et al*. (2017). Generation time (i.e. the average time between two consecutive generations in the lineages of a population) data were retrieved from the IUCN database (http://www.redlist.org/, August 2018; see Appendix 2). For the present study, geographic range data was compiled as a surface area of geographic ranges (in km^2) and these pieces of information were recovered from IUCN (2010). To conclude, we documented maximum altitude, maximum diameter and maximum height for all cycads from IUCN (2010) as well. In general, eight variables were included in the predictive model (here SEM: see Data analysis section below for further explanation) and all their values are well presented in Appendix 2.

3.3 Data analysis

All analyses used for this work were carried out in R (R Core Team, 2015) in the library piecewiseSEM (Lefcheck, 2016), and the correlations amongst all variables were checked to stay away from repetition. The analysis on the SEM model was simply focused on the eight above-mentioned variables for analyzing data (see figure 5 below for a full explanation of SEM model).

3.3.1 Statistical analysis

3.3.1.1 The use of Structural Equation Modeling (SEM) to explain threat status of cycad species

SEM model implemented in the R library piecewiseSEM (Lefcheck, 2016) was used to study the patterns of extinction risk for global cycad species. SEM model in this study was built for statistical analysis to assess the relationships between all variables mentioned above. Nevertheless, SEM is a probabilistic model that can join numerous predictors and responses variables in a sole causal system (Lefcheck, 2016) and it was done on the meta-models built based on some assumptions predicted (Figure 2). However, SEM model is frequently represented by using path diagrams (multivariate procedure), where arrows designate the direction of relationships between observed variables. So, these relationships (i.e. positive: direct and negative: indirect) are taken in a progression of structured equations that match to the pathways in the model. It is also a method of expressing causal relations between variables via a set of equations (Grace *et al*., 2012; 2015). In addition, SEM model requests a change in how ecological and evolutionary questions are well organized and tried with an emphasis on the current assessment of several causal hypotheses inside a solitary network (Lefcheck, 2016).

Lefcheck (2016) then illustrated two primary characteristics of SEM that help to isolate them from conventional modeling approaches. Firstly, paths stand for hypothesized causal relationships and this characteristic demonstrates that predictors (dependent variables: maximum altitude, maximum diameter, number of threats, ED, generation time, geographic range and maximum height for this case) could cause the response (independent variable: IUCN threat status) and vice versa, or both may be a result of a third (unmeasured) variable. Secondly, these variables can both look as predictors and responses. SEM is useful to test and quantify the indirect impacts that would otherwise go unrecognized by any single model, and one variable to fill in as a response in one path or as a predictor in another (Grace *et al*., 2012). The test of directed separation was led in joining all *P*-values across the premise set in a test statistic, Fisher's *C*. Moreover, the implication of any given independent claim that is its *P*-value could be assessed and isolated. Thereafter, the global goodness-of-fit of the SEM in this study was assessed using a chi-square test to compare the assessed values to the observed covariance matrix (see also Grace, 2006). This method (the goodness-of-fit) tested the supposition that all variables are restrictively independent, and there were no missing relationships among variables that are not associated (Appendix 3; see Shipley, 2000). As demonstrated by Shipley (2013), the Fisher's *C* statistic was utilized to get an estimation of Akaike's information criterion (AIC) and its scores were computed to conduct goodness-of-fit tests for both the full and part models (SEM; Appendix 3).

CHAPTER 4

RESULTS

4.1 Presentation of the results

In this present study, SEM approach was employed to reach the objective. The main model built includes all eight variables by fitting the predictors and responses (see Figure 4 for the full model). However, seven variables (i.e. ED, maximum altitude, number of threats, range, maximum height, generation time and maximum diameter) are predictors to IUCN threat status, which is the only dependent variable (see Material and Method and Figure 5 below). The model reveals three different arrows with positive and negative prediction respectively.

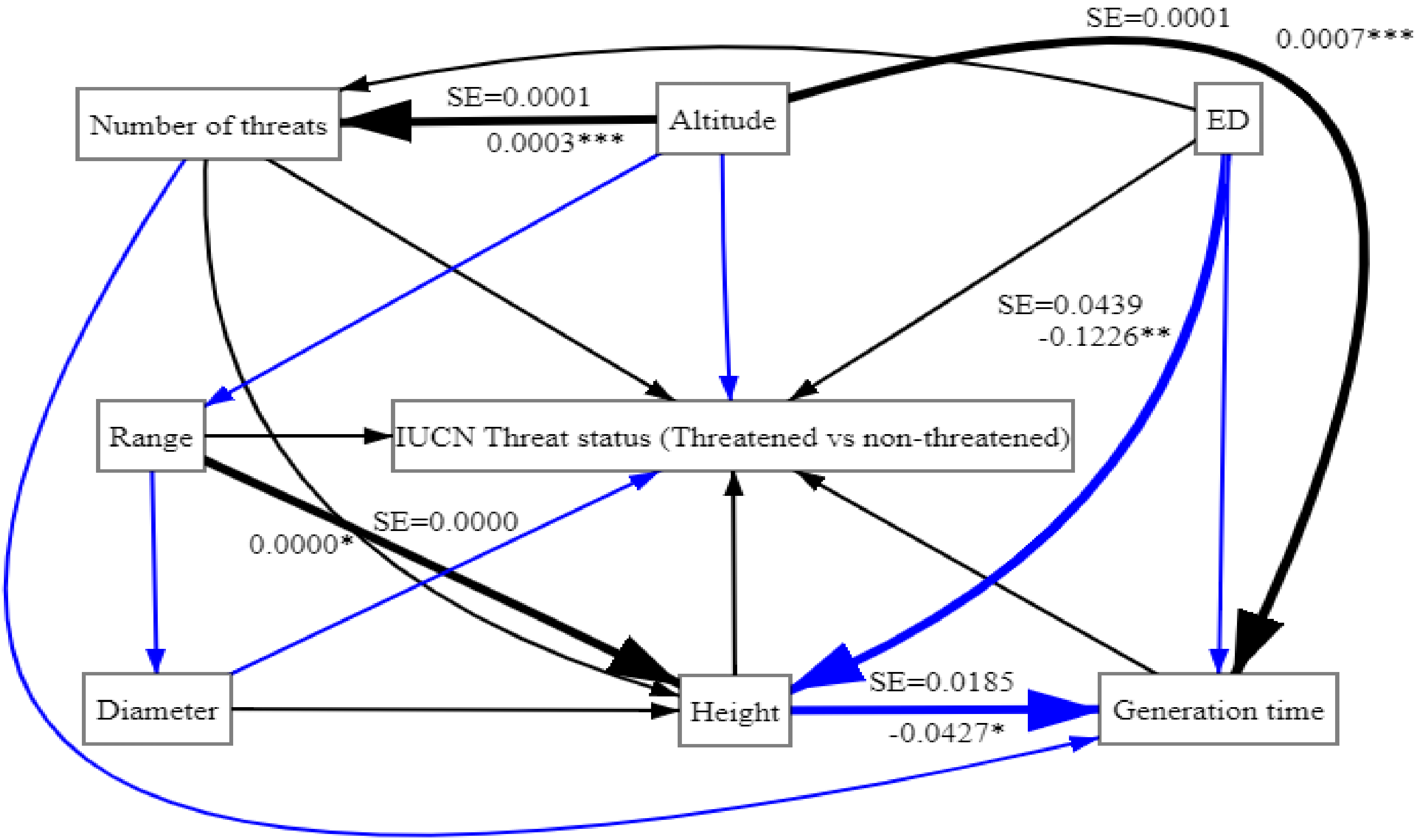

Figure 5: Meta-model illustrating the potential influence of predictors towards responses among variables (SEM).

Different paths (arrows) in this figure 5 above represent unidirectional relationships between variables (predictors towards responses). However, they are colour-coded: black arrows (direct path) denote the positive relationships between two variables; blue arrows (indirect path) denote the negative relationships between two variables, and thickness denotes that the relationship between two variables is significant. The width of arrows is indicative of the strength of the relationships between two variables. Values on the arrows are path coefficients (β) (see also Table 2 for all path coefficients as well as SE: Standard error of all variables). In figure 5, the report was only based on path coefficients (β) and SE for variables that are significant.

However, the SEM model (Figure 5) identified four variables in five predictions that significantly correlate with the extinction risk (thick paths). According to the model (results), these values show that cycad species tend to be more at risk of extinction. In fact, among these relationships, two correlate positively (i.e. range, which predicts maximum height and maximum altitude, which predicts two other variables such as number of threats and generation time). Besides, two other variables do correlate negatively (i.e. ED that have significant relationships with maximum height and maximum height also do predict generation time). Nonetheless, these variables, as well as their significant values, are as presented below. Maximum altitude towards number of threats (β= 0.0003; SE= 0.0001; $p \leq 0.01$). Range (km^2) towards height maximum (β= 0.0000; SE= 0.0000; $p \leq 0.05$). ED towards height maximum (β= -0.1226; SE= 0.0439; $p \leq 0.01$). Height maximum towards generation time (β= -0.0427; SE= 0.0185; $p \leq 0.05$). Finally, altitude maximum towards generation time (β= 0.0007; SE= 0.0001; $p \leq 0.001$: Figure 5 and Table 1).

Table I: Predictor and response variables for extinction risk.

Significant variables are indicated by stars (*) and the number of stars indicates the significant level.

Significant codes : 0, '***' 0.001, '**' 0.01, '*' 0.05.

Response	Predictor	Estimate	Std. Error	Df	Crit. Value	P. value	Std. Estimate
Number of threats	Maximum altitude	0.0003	0.0001	152	2.8512	0.0044	NA **
Number of threats	ED	0.0040	0.0045	152	0.8994	0.3684	NA
Range (Km^2)	Maximum altitude	-23.9837	15.9542	33	-1.5033	0.1423	-0.0109
Maximum diameter	Range (Km^2)	0.0000	0.0000	68	-0.1235	0.9020	-0.0139
Maximum height	Maximum diameter	-0.1222	0.3823	46	-0.3197	0.7507	-0.0239
Maximum height	Range (Km^2)	0.0000	0.0000	46	2.0706	0.0440	0.1465 *

Maximum height	Number of threats	-0.6023	0.4869	46	-1.2370	0.2224	-0.1067
Maximum height	ED	-0.1226	0.0439	46	-2.7925	0.0076	-0.2576 **
Generation time	Maximum height	-0.0427	0.0185	109	-2.3057	0.0211	NA *
Generation time	ED	-0.0024	0.0055	109	-0.4371	0.6620	NA
Generation time	Maximum altitude	0.0007	0.0001	109	6.3254	0.0000	NA ***
Generation time	Number of threats	-0.0586	0.0570	109	-1.0283	0.3038	NA
Threat status	Number of threats	12.4026	84748.9242	18	0.0001	0.9999	0.0294
Threat status	Range (Km^2)	0.0059	47.7173	18	0.0001	0.9999	16.3384
Threat status	Maximum	-389.8862	4060109.7464	18	-0.0001	0.9999	-1.0184

	diameter						
Threat status	Maximum height	46.9068	271180.4043	18	0.0002	0.9999	0.6271
Threat status	Generation time	0.5167	2397.7656	18	0.0002	0.9998	0.1218
Threat status	ED	0.6093	5374.3976	18	0.0001	0.9999	0.0171
Threat status	Maximum altitude	-0.1709	585.1662	18	-0.0003	0.9998	-0.2163

Moreover, at the IUCN category level, the findings that some variables are great predictors of different IUCN threat status in the Nagelkerke method. However, two variables (number of threats and maximum diameter) have the lower rate to fit the model with 9% and 0% respectively, while maximum height and geographic range are the good predictors of extinction risk with 99% and 48% each. Conversely, two variables (i.e. threats status and geographic range) were considered as perfect predictive of extinction risk with R-square of 100% each (Table 3 below).

Table III: Individual R-squared of variables for the fitting SEM model

Response	**Method**	**R. Squared**
Number of threats	Nagelkerke	0.09
Range (km^2)	Nagelkerke	1.00
Maximum diameter	Nagelkerke	0.00
Maximum height	Nagelkerke	0.99
Generation time	Nagelkerke	0.48
Threat status	Nagelkerke	1.00

The results in Table 3 for prediction of a model (R^2s for segment models given in the response variables) show that the majority of cycad species are threatened. Specifically, based on the maximum height that exhibited the highest predictive power (99%) in SEM model. However, this analysis of SEM revealed a perfect global goodness-of-fit by explaining the threat level of cycad species (Fisher's C = 13.776, df = 16, P = 0.615; Appendix 3). In comparison with SEM model fitted with maximum likelihood (see also Grace, 2006), the model showed that Akaike's information criterion (AIC) has a lower value (73.776) than Bayesian information criterion (BIC) value

(111.519). Consequently, this result of smaller AIC value reveals that the model is considered as true because there are no significant variables shown in all these *P*-values (see Appendix 3). Nonetheless, this test of directed separation that includes global goodness-of-fit is confirmed to be a good fitting model simply because it needed the adequate capacity to discard the null (Lefcheck, 2016) (i.e. *P*-values for all paths are > 0.05; Appendix 3).

Lastly, the pre-disposition of cycads to the risk of extinction was investigated on some groups of threats [habitat loss (destruction), deforestation, medicinal usages, over-collection (poaching), fire, grazing, invasive alien plants, reproduction failure and flood/drought; see Mankga and Yessoufou, 2017]. Then for these variables, only four variables in five predictions were found to be significant in driving the extinction risk of cycad species.

CHAPTER 5

DISCUSSIONS

The result of this study by using the SEM model indicated that cycad species are facing a great threat at the global scale. The effectiveness of this method relies on how fast cycad species are facing the extinction risk and the patterns that are driving them to such risk. Likewise, it also showed how variables were either predictors or responses among them in different paths (arrows). However, below are the explanations of all relationships (positives or negatives) amongst different variables used in this present study.

5.1 Positive relationships amongst variables

The fitting meta-model on SEM for eight variables above mentioned (Figure 5, Table I) in the biological, ecological and evolutionary information of cycads was built to test the correlation among these variables and the extinction risk of cycads. However, the results using SEM analysis revealed a perfect fit of this meta-model in explaining the threat level of cycad species (Fisher's C = 13.776, df = 16, P = 0.615; Appendix 3). In this section, only positive relationships among variables are reported, with a specific accent made on variables that have significant relationships. Nevertheless, maximum altitude has a positive relationship with two other variables: number of threats and generation time as expected in the theory (improvement of the hypothesis), but after analysis these relationships became significants. The availability expectation that species found in elevated areas might have a chance to survive longer generation time, simply because they will be far away from human (poachers) and invasive plants as well as environmental impact such as floods. This result confirms the idea of Fjeldsã and Lovett (1997) and Fjeldsã *et al*. (2012) that higher altitudes (i.e. mountains) are seen to be considered as 'safe havens' for threatened species. Surprisingly, in their work, Yessoufou *et al*. (2012) got the opposite outcomes by discovering a greater richness of threatened taxa at elevated altitudes. The results show that geographic range (km^2) has positive relationships with two other variables such as threat status and maximum height (availability of theoretical model). However, this relationship with maximum height is mentioned to be significant. The expectation that species occurring in lower altitude might have a considerable number of threats because they might be threatened by human activities (over-collection, deforestation, medicine usage, invasive plants, fire, etc.) as well as flood and drought. This finding of cycad to be threatened by invasive (alien) plant species support the work of Donaldson (2003) that demonstrated how alien species, especially in the African continent, were driving the decline of cycad in the long term. Mankga and Yessoufou (2017) also reported in their work that invasive species are among the drivers of cycad at a global scale, the support of the result of this present work. The finding that cycad species, being at risk of extinction is not a surprise simply because they are facing a high number of threats. This supports the study of Yessoufou *et al*. (2017), confirming that ~70% of cycads species are threatened with a high risk of extinction.

Maximum height has positive relationships with threat status as well and this confirms the theoretical model. As expected that species with high height could invest more in length and become the first target by poachers because they will be easily perceived. As consequence, they would not have a chance to survive longer. Nonetheless, ED has a positive relationship with two other variables: number of threats and threat status (the support of theoretical model expectation). The expectation that species with high-ED level would be exposed to the risk of extinction. Many literatures do confirm this expectation of high-ED species to be exposed to a high risk of extinction as well. A good example was firstly made for animals, especially vertebrates (e.g. mammals: Isaac *et al.,* 2007; updated by Davies and Yessoufou, 2013; Luiz *et al.,* 2016, birds: Jetz *et al.,* 2014, reptiles: Isaac *et al.,* 2012; Veron *et al.,* 2016, and fish: Adeoba *et al.,* 2019), then for plants, especially cycads (Yessoufou *et al*., 2017). This work of Yessoufou *et al*. (2017) was considered as the first-ever in relating the pattern of high-ED cycad species to be threatened.

5.2 Negative relationships amongst variables

The fitting meta-model on SEM (as mentioned above) revealed also negative relationships amongst variables. As explained above, the results on this SEM analysis revealed a perfect fit of this meta-model in explaining the threat level of cycad species (Fisher's $C = 13.776$, df = 16, $P = 0.615$; Appendix 3). However, contrary to the above section, the latter will only focused on variables that have negative relationships among them and of course in making a specific accent on significant variables.

For instance, the results revealed that ED has a negative but significant relationship with maximum height (not supporting the theoretical model) as the expectation that species with high-ED score would be at risk of extinction, means they will invest in length and would be exposed to risk. Likewise, the result of meta-model shows again that ED has a negative relationship with generation time. Maximum altitude has a negative relationship with geographic range (km^2) and IUCN threat status (availability of theory). The expectation that species in elevated altitude might have a chance to not being threat and could survive longer generation time, simply because they would be far away from poachers and environmental impact (floods) as well as invasive plants. Nevertheless, as explained above, Yessoufou *et al* (2012) found the opposite findings. Subsequently, the negative relationship between altitude and extinction risk might likewise be the consequences in the relationship that was established for maximum diameter (Mankga and Yessoufou, 2017). The latter (maximum diameter) also has negative relationships with two other variables (i.e. maximum height and IUCN threat status) as expected. The expectation that a species with a huge diameter will not invest more in height and will be the target for poachers especially for medicinal purposes and would also be affected by fire.

Geographic range (km^2) has negative relationships with maximum diameter, which not support the expectation of the theoretical model. It seems plausible that species found in lower altitude might have a considerable number of threats simply because they would be easily spotted by illegal poachers (over-collection, deforestation, medicine usage, etc.) and also exposed to other environmental extinction drivers (i.e. flood, drought). Number of threat has a negative relationship with generation time. Maximum height has a negative but significant relationship with generation time. The expectation that species with high height would invest more in length and of course, would be perceived by poachers and become their first target.

5.3 The priority of ED score ranking on cycads and their IUCN category

Numerous studies that address the matter for prioritising high-ED species over every taxonomic group were completed to escape the loss of evolutionary diversity. Some of them were made for vertebrates (as above explained). For this study, Yessoufou *et al*., (2017) list was used as reference to present the ranking of each cycad species based on their ED scores, so that high-ED species are those that merit specific attention (Faith*,* 1992). In this ranking, *Microcycas calocoma* stands in the top species on the global ED list (98.762 MY: Appendix 2). Therefore, this species is required to be given priority in conservation programme organized by decision-makers and therefore merits a short exhibition to attract their attention. Nevertheless, this species is endemic to Cuba (See Appendix 1) and is IUCN-categorized as Critically Endangered (IUCN, 2010) where it faces anthropogenic pressures (i.e. overcollection, medicinal usage, agriculture, etc.) as well as reproductive failure due to pollinator extinction (Tafirei, 2016). Also, *M. calocoma* appears to be a monospecific genus which is on Appendix I of the CITES appendices and is found within protected areas (Vinales National Park and/or Mil Cumbres) as well as the National Botanical Garden of Cuba (IUCN, 2010). In addition, *Chigua bernalii* (CR: 92.778 MY), *Stangera eriopus* (VU: 86.066 MY), *Zamia vazquezii* (CR: 66.921 MY) as well as *Cycas balansae* (NT: 60.965 MY) are well represented in the top ED.

The top 50% ED species comprises 15 CR (30%), 10 EN (20%) and 12 VU (24%) and, in the top 100 ED species, there are 29 CR (29%), 20 EN (20%) and 21 VU (21%), which suggest that the top ED species are threatened species as well (Appendix 1). With regard to their taxonomy, the leading genera in top 50% ED are *Cycas* (12 species) and *Zamia* (11 species), followed by *Ceratozamia* (eight species), *Encephalartos* (seven species) and *Macrozamia* (three species). Likewise, *Bowenia*, *Dioon* and *Lepidozamia* have each two species respectively in the top 50% ED, while *Chigua*, *Microcycas* and *Stangeria* have only one species each (Appendix 2). Once all (339) taxa are considered, there are 67 (CR), 70 (EN), 78 (VU), 68 (NT), 47 (LC), five (DD) and four (EW), signifying that 215 species are threatened and 115 are non-threatened, with five species having an unknown threat status (i.e. DD species: Yessoufou *et al*., 2017) and four species being already extinct in the wild (see Appendix 1)

To end with, this present study on cycad species offers an occasion to discover how ED score is distributed through IUCN categories. However, the outcomes of this present work revealed that there is a relationship between ED scores and IUCN category of global cycad species. As such, this investigation based on ED scores, support the finding shown in Yessoufou *et al*. (2017), which boosts this general pattern (i.e. the loss of high-ED species would cause an unequal loss of evolutionary diversity). In contrary, the work of Adeoba *et al*. (2019) on African fish (Cyprinidae) revealed that there is no relationship between ED scores and IUCN categories as well as other preceding studies on various vertebrate ancestries (see Tonini *et al*., 2016 for reptiles; Arregoitia *et al*., 2013 or Warren *et al*., 2008 for mammals and Jetz *et al*., 2014 for birds). Findings of this work that cycad species are more evolutionarily distinct than vertebrates' species and support efforts to secure species in this clade (Yessoufou *et al*., 2017). Therefore, the protection of high-ED species may prompt the preservation of particularly divergent genomes (Warren *et al*., 2008).

5.4 The limit of regional protection actions for the top ED species

Zamia is a genus that is endemic in the New World, and 11 of its species are in the top 50% of ED score, whilst 27 species are in the top 100. The first is *Zamia vazquezii* (4th position on global ED score) and it occurs in Veracruz State (Mexico). The finding that this species is amongst the top three Americans and 4th on global ED (Appendix 2) priority species necessitate a renewed pledge for stronger safeguarding measures from conservation decision-makers. Being a CR species, this cycad species is threatened by habitat loss (deforestation) and there are no more 50 mature plants. Besides, even though efforts are made to preserve this genus, a great deal still needs to be undertaken for those species with high ED scores (top 100), because they still outside protected areas. A good example is *Zamia monticola,* which is amongst the species that have shown a decline of over 80% during the past 60 years (IUCN, 2010), but are still found outside protected areas.

The genus *Ceratozamia*, the 22nd most species-rich in the ED species is, like *Zamia,* native to the New World, and their 27 extant species are endemic to Mexico, Guatemala, Honduras and Belize (all listed under CITES Appendix I; Whitelock, 2002). They have eight species in the top 50 ED and 14 of them occurs in the top 100 and strong procedures have been taken to preserve this genus from the loss (Chavez *et al.,* 1998).

The monophyletic species *Stangeria eriopus* stands the first on the African continent and 3rd on a global scale in both top 50 and 100 ED. It occurs in South Africa, especially in the provinces of Eastern Cape and KwaZulu-Natal (Osborne, 2003). The genus *Encephalartos* has seven species in the top 50 of ED score and 17 in the top 100. The first is *E. brevifoliolatus* (12th position on global ED score and 2nd in Africa) which just occurs on a single granite mountain in the Limpopo province of South Africa. This species is extinct in the wild because of the lack of protection measures to stop human activities such as intense poaching, over-collection, medicinal usages, etc. (IUCN, 2010, Bamigboye, 2017). Even if some of them are found in protected areas, there is still an increasing need to revisit their boundaries' networks to include species that require particular attention (Heller *et al.,* 2009).

Asian cycads have a considerable number at global top ED (12 species in top 50 and 24 species in top 100 respectively) and are least found in protected areas. The top in the group of Asian cycads is *Cycas balansae* (5th in global ranking ED; Appendix 2).

Either apart from *Cycas hainanensis* found in Tongguling National Nature Reserve in China, the rest in the top 100 ED species are not in protected areas or do not have any evaluated information concerning their protection status (IUCN, 2010).

Macrozamia genus, which is found in Australasia, showed only nine species in the top 100 ED. *Macrozamia cranei* is the first in ranking on the continent and ranks 10th globally in the top ED species. This species, however, has been destroyed during the clearing of forest for agriculture and grazing. Of these, *Macrozamia elegans* is protected in the Blue Mountains National Park (IUCN, 2010).

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Earth is experiencing the sixth mass extinction period characterized by an unprecedented loss of biodiversity (Millenium Ecosystem Assessment, 2005; Ricketts *et al.,* 2005; Vamosi and Vamosi, 2008). Consequently, there is an urgent need for a continued commitment towards reducing the ongoing rapid loss of biodiversity on which humanity relies for medicine, food, pollination, recreation, etc. (Millenium Ecosystem Assessment, 2005). However, there is a biogeographic pattern in the loss of biodiversity such that most threatened species (cycads included) are found in tropical regions (Vamosi and Vamosi, 2008). The rising pattern in extinction risk shows that threatened species are clustered on a phylogeny (Purvis *et al.,* 2000; Yeassoufou and Davies, 2016), and their loss would prune seriously the branch of the tree of life (Davies, 2015). This pattern has appeared for both angiosperm and vertebrates. For gymnosperm (here cycads), it has been demonstrated that the risk of extinction is not grouped on the cycad tree of life and the loss of top ED species would reduce more PD than expect. This suggests that a better understanding of the diversification forces of a given lineage is required if we are to provide well-informed decisions for conserving biodiversity. For this study, the pattern driving the extinction risk of this group of plants were investigated to inform conservation decisions. By doing so, this work elucidated that human activities are considered as the main drivers. A list of variables to fit the predictive model (here SEM) was also compiled as well as IUCN status for all cycads. Considering the inability to preserving all species worldwide simultaneously in an efficient manner, priority for the conservation efforts must be given to species that represent particular attention (e.g. species with high-ED values: Jetz *et al.,* 2014; Redding *et al.,* 2014; 2015).

6.2 Recommendations

The present study is the best suited to inform conservation decisions for the rapid loss of cycad species. So that the efforts to safeguard cycads based on IUCN threat categories would contribute to preserving high-ED species as well. In general, conservation actions, that put together *in situ* and *ex situ* conservation programs need to be increased to guarantee that high-ED cycads are protected all over the world. These high-ED cycad species might slide into extinction unnoticed - there is, therefore, a need for global ED campaign similar to the ongoing ED campaign done for Vertebrates (Jetz *et al.,* 2014; Redding *et al.,* 2010).

We recommend conservation decision-makers to draw a bigger picture for the global conservation plans for cycads, to prevent their extinction. Cycad legislation should then be introduced at both global and local level and implement the regulation of human-cycad interactions.

REFERENCES

- Adeoba, M. I., Tesfamichael, S. G. & Yessoufou, K. (2019): Preserving the tree of life of the fish family Cyprinidae in Africa in the face of the ongoing extinction crisis. *Genome*, 62: 170–182. dx.doi.org/10.1139/gen-2018-0023.

- Achard, F., Eva, H. D., Stibig, H. J., Mayaux, P., Gallego, J., Richards, T. & Malingreau, J. P. (2002): Determination of deforestation rates of the world's humid tropical forests. *Science,* 297: 999–1002.

- Anderson, J. M., Anderson, H. M. & Cleal, C. J. (2007): Brief history of the gymnosperms: classification, biodiversity, phytogeography and ecology. *Strelitzia,* 20. *South African National Biodiversity Institute*, Pretoria.

- Artabe, A., Stevenson, D. W. (1999): Fossil Cycadales in Argentina. *Bot Rev*. 65: 219–238.

- Arhonditsis, G. B., Stow, C. A., Steinberg, L. J., Kenney, M. A., Lathrop, R. C., McBride, S. J. & Reckhow, K. H. (2006): Exploring ecological patterns with structural equation modeling and Bayesian analysis. *Ecological Modeling*, 192: 385-409.

- Baillie, J. E. M., Hilton-Taylor, C. & Stuart, S. N. (2004): A global species assessment. IUCN, Gland, Switzerland.

- Bamigboye, S. O., Tshisikhawe, P. M. & Taylor, P. J. (2016): Review of extinction risk in African cycads. *Phyton International Journal of Experimental Botany,* 85: 333–336.

- Bamigboye, S. O., Tshisikhawe, P. M. & Taylor, P. J. (2017): Detecting threats to *Encephalartos transvenosus* (Limpopo cycad) in Limpopo province, South

Africa through indigenous knowledge. *Indian Journal of Traditional Knowledge,* 16(2): 251–255.

- Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O. U., Swartz, B., Quental, T. B., Marshall, C., McGuire, J. L., Lindsey, E. L., Maguire, K. C., Mersey, B. & Ferrer, E. A. (2011): Has the Earth's sixth mass extinction already arrived? *Nature,* 471 (7336): 51 – 57. DOI: 10.1038/Nature09678.

- Belkhiri, L. & Narany, T. S. (2015): Using multivariate statistical analysis, geostatistical techniques and structural equation modeling to identify spatial variability of groundwater quality. *Water Resour Manage* (29):2073–2089. DOI 10.1007/s11269-015-0929-7.

- Bennett, P. M. & Owens, I. P. F. (1997): Variation in extinction risk among birds: chance or evolutionary predisposition. Proceedings of Royal Society London. *Biology*, 264:401–408.

- Bielby, J., Cunningham, A. A. & Purvis, A. (2006): Taxonomic selectivity in Amphibians: Ignorance, geography or biology? *Animal Conservation,* 9:135–143.

- Bland, L. M., Collen, B., Orme, C. D. L. & Bielby, J. (2014): Predicting the conservation status of data-deficient species. *Conserv. Biol*. 29:250–259.

- Bogler, D. J. & Fransisco-Ortega, J. (2004): Molecular systematic studies in cycads, evidence from *trnL* and ITS2 rDNA sequences. *The Botanical Review*, 70: 260-273.

- Bollen, K. A. (1989): Structural equations with latent variables.*John Wiley and Sons*, New York.

- Bonta, M. (2010): Human geography and ethnobotany of cycads in Xi'ui, Teenek, and Nahuatl communities of northeastern Mexico. Final Report. Cleveland.

- Bradshaw, C. J. A., Giam, X., Tan, H. T. W., Brook, B. W. & Sodhi, N. S. (2008): Threat or invasive status in legumes is related to opposite extremes of the same ecological and life history attributes. *Journal of Ecology,* 96:869–883.

- Brenner, E. D., Stevenson, D. W. & Twigg, R. W. (2003): Cycads: Evolutionary innovations and the role of plant-derived neurotoxins. *Trends in PlantScience*, 8:446-452.

- Brummitt, N. A., Bachman, S. P., Griffiths-Lee, J., Lutz, M., Moat, J. F. & Farjon, A. (2015): Green Plants in Red: A baseline Global Assessment for the IUCN Sampled Red List Index for Plants, *Plos One,* 10, e0135152.

- Butchart, L. A., Stattersfield, A. J., Baillie, J., Bennun, L. A., Stuart, S. N., Akçakaya, H. R. & Mace, G. M. (2005): Red List Indices to measure progress towards the 2010 target and beyond. *Philosophical Transactions of the Royal Society B*, 360: 255–268.

- Cafaro, P. (2015): Three ways to think about the sixth mass extinction. *Biological Conservation*, 195: 387-393.

- Cardillo, M. (2003): Biological determinants of extinction risk: why are smaller species less vulnerable? *Animal Conservation*, 6: 63–69.

- Cahill, A. E., Aiello-Lammens, M. E., Fisher-Reid, M. C., Hua, X., Karanewsky, C. J., Yeong Ryu, H., Sbeglia, G. C., Spagnolo, F., Waldron, J. B., Warsi, O. & Wiens, J. J. (2013): How does climate change cause extinction? *Proc R Soc B,* 280: 20121890.

- Calonje, M., Kay, J. & Griffith, M. P. (2011): Propagation of cycad collections from seed: Applied reproductive biology for conservation. *Sibbaldia*, 9: 77-96.

- Calonje, M., Stevenson, D.W. & Stanberg, L. (2017). The World List of Cycads, online edition. Available from: http://www.cycadlist.org (Accessed on 10 April 2018).

- Cardillo, M. (2003): Biological determinants of extinction risk: why are smaller species less vulnerable? *Animal Conservation,* 6: 63–69.

- Ceballos, G., Ehrlich, P. R., Barnosky, A. D., García, A., Pringle, R. M. & Palmer, T. M. (2105): Accelerated modern human–induced species losses: Entering the sixth mass extinction. *Sci. Adv*. 1, e1400253.

- Cequinel, A., Capellesso, E.S., Marcilio-Silva, V., Cardoso, F.C.G. & Marques, M.C.M. (2018): Determinism in tree turnover during the succession of a tropical forest. Perspectives in Plant Ecology*, Evolution and Systematics,* 34: 120–128.

- Chamberlain, C. J. (1925): The origin of cycads. *Science New Series,* 61: 73-77.

- Chaw, S. L. & Gaston, K. J. (2005): Areas, cradles and museums: The latitudinal gradient in species richness. *Trends in Ecology and Evolution,* 15: 311-315.

- Chaw, S. M., Walters, T. W., Chang, C. C., Hu, S. H. & Chen, S. H. (2005): A phylogeny of cycads (Cycadales) inferred from chloroplast *matK* gene, *trnK*, and nuclear rDNA ITS region. *Molecular Phylogenetic and Evolution*, 37: 214-234.

- Christensen, R. H. B. (2013): Package “Ordinal”: regression models for ordinal data.*Copenhagen, Denmark*. (Version 2012-09-11).

- Cibrian–Jaramillo, A., Daly, A. C., Brenner, E., Desalle, R. & Marler, T. E. (2010): When North and South do not mix genomic connectivity of a recently endangered oceanic cycad. *Cycas micronesica*, in Guam using EST-microsatellites. *Molecular Ecology*, 19(12): 2364-2379.

- CITES (2012): Text of the Convention. http://www.cites.org/eng/disc/text.php#II.

- CITES (2015): Appendices. http://www.cites.org/eng/app/appendices.php.

- Condamine, F. L., Rolland, J. &Morlon, H. (2013): Macro-evolutionary perspectives to environmental change. *Ecology Letters*, 16:72–85.

- Condamine, F. L., Nagalingum, N. S., Marshall, C. R. & Morlon, H. (2015): Origin and diversification of living cycads: A cautionary tale on the impact of the branching process prior in Bayesian molecular dating. *BMCEvolutionary Biology*, 15:65.

- Cooper, N., Bielby, J., Thomas, H. G. & Purvis, A. (2008): Macroecology and extinction risk correlates of frogs. *Global Ecology and Biogeography*, 17:211–221.

- Cousins, S. R., Williams, V. L. & Witkowski, E. T. F. (2012): Uncovering the cycad taxa (*Encephalartos* species) traded for traditional medicine in Johannesburg and Durban, South Africa. *South African Journal of Botany,* 78: 129-138.

- Cousins, S. R. & Witkowski, E.T. F. (2017): African Cycad Ecology, Ethnobotany and Conservation: A Synthesis. *Bot. Rev*. 1-43.

- Crepet, W. L. & Niklas, K. J. (2009): Darwin's second "abominable mystery": why are there so many angiosperm species? Am*. Journal of Botany*, 96: 366–381.

- Crisp, M. D. & Cook, L. G. (2011): Cenozoic extinctions account for the low diversity of extant gymnosperms compared with angiosperms. *New Phytol*, 192: 997–1009.

- Da Silva, J. M., Donaldson, J. S., Reeves, G. & Hedderson, T. A. (2012): Population genetics and conservation of critically small cycad populations: A case study of the Albany Cycad. *Encephalartos latifrons* (Lehmann). *Biological Journal of the Linnean Society,* 105: 293-308.

- Daly, B., Donaldson, J. S., Friedmann, Y., Hahndiek, Q., King, N., Newton, D. & Southwood, A. (2006): Albany cycad (*Encephalartos latifrons*) population and habitat viability assessment workshop report. *Conservation breeding Specialist group (SCC/IUCN)/CBSG Southern Africa*. Endangered Wildlife Trust, Johannesburg.

- Dantas, V. L. & Pausas, J. G. (2013): The lanky and the corky: fire-escape strategies in savanna woody species. *Journal of Ecology,* 101: 1265–1272.

- Daru, B. H., Yessoufou, K., Mankga, L. T. & Davies, T. J. (2013): A global trend towards the loss of evolutionary unique species in Mangrove ecosystem. *PLoSONE,* 8: e66686.

- Daru, B. H., Van der Bank, M. & Davies, T. J. (2015): Spatial incongruence among hotspots and complementary areas of tree diversity in southern Africa. *Diversity and Distribution*, 21: 769–780.

- Daru, B. H. & le Roux, P. C. (2016): Marine protected areas are insufficient to conserve global marine plant diversity. *Global Ecology and Biogeography*, 25: 324–334.

- Davies, T. J. & Cadotte, M. W. (2011): Quantifying biodiversity – does it matter what we measure? In: Zachos, F. E., Habel, J. C (eds) Biodiversity hotspots. *Springer, Heidelberg*, 43–60.

- Davies, T. J., Smith, G. F., Bellstedt, D. U., Boatwright, J. S., Bytebier, B., Cowling, R. M., Forest, F., Harmon, L. J., Muasya, A. M., Schrire, B. D., Steenkamp, Y., van der Bank, M. & Savolainen, V. (2011): Extinction risk and diversification are linked in a plant biodiversity hostspot. *PLoS Biology,* 9: e1000620.

- Davies, T. J. & Yessoufou, K. (2013): Revisiting the impacts of non-random extinction onthetree-of-life. *Biology Letters*, 20130343.

- Davies, T. J. (2015): Losing history: how extinctions prune features from the tree-of-life. *Philos. Trans. R Soc B,* 370. Doi: 10.1098/rstb.2014.0006.

- DEAT. (2010): General Notice 416: Draft biodiversity management plan for *Encephalartos latifrons*. National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004), *Government Gazette,* 552: 33456.

- DEAT (2012): General Notice 371: Prohibition of trade in certain *Encephalartos* (cycad) species. National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004), *Government Gazette,* 563: 35344.

- de Albuquerque, U.P. (2006): Re-examining hypotheses concerning the use and knowledge of medicinal plants: a study in the Caatinga vegetation of NE Brazil. *Journal of Ethnobiology and Ethnomedicine*, 2(1), 30.

- de Laubenfels, D. J. & Adema, F. (1998): A taxonomic revision of the genera *Cycas* and *Epicycas* gen. nov. (Cycadaceae*). Blumea,* 43: 351-400.

- Dirzo, R. & Raven, P. J. (2003): Global state of biodiversity and loss. *Annu Rev Environ Resour*, 28: 137–167.

- Donaldson, (2003): *Cycads. Status Survey and Conservation Action Plan*. IUCN/SSC. Cycad Specialist Group. IUCN, *Gland, Switzerland and Cambridge*, UK, ix + 86 pp.

- Donaldson, J. S., Hill, K. D. & Stevenson, D. W. (2003): Cycads of the world: an overview. In: Donaldson JS (eds) Cycads. Status survey and conservation action plan. IUCN/SSC. Cycad Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK, pp 3-8.

- Donaldson, J. S. (2008): South African *Encephalartos* species. NDF workshop case studies: Case study 4: *Encephalartos*. Mexico.

- Doyle, J.A. & Donoghue, M.J. (2012): Fossils and seed plant phylogeny reanalyzed. *Brittonia,* 44: 89-106.

- Etherington, R., Jeffers, B., Grigg, L. & Paddock, A. (2018): Investigating the demographics and intrapopulation spatial patterns of the endangered *Cycas megacarpa* K.D. Hill in central Queensland, Australia. *Austral Ecology,* 43: 110–116.

- Faith, D. P. (1992): Conservation evaluation and phylogenetic diversity. *Biological conservation*, 61: 1-10.

- Fisher, D. O. & Owens, I. P. F. (2004): The comparative method in conservation biology. *Trends Ecology Evolution*, 19:391–398.

- Fjeldsã, J., Bowie, R.C. & Rahbek, C. (2012): The role of mountain ranges in the diversification of birds. Annual Review of Ecology, *Evolution andSystematics,* 43:249–265.

- Fjeldsã, J. & Lovett, J. C. (1997): Geographical patterns of old and young species in African forest biota: the significance of specific montane areas as evolutionary centres. *Biodiversity and Conservation*, 6:325–346.

- Foden, W. B., Butchart, S. H. M., Stuart, S. N., Vie, J-C., Akçakaya, H. R., Angulo, A., DeVantier, L.M., Gutsche, A., Turak, E., Cao, L., Donner, S. D., Katariya, V., Bernard, R., Holland, R. A., Hughes, A. F., Hanlon, S. E. O., Garnett, S. T., Sekercioglu, C. H. & Mace, G. M. (2013): Identifying the World’s most climate change vulnerable species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals.*PLoS ONE,* 8 (6): e65427. Doi: 10.1371 /journal.pone.0065427.

- Fragnière, Y., Bétrisey, S., Cardinaux, L., Stoffel, M. & Kozlowski, G. (2015): Fighting their last stand? A global analysis of the distribution and conservation status of gymnosperms. *Journal of Biogeography*, 42: 809-820.

- Freville, H., McConway, K., Dodd, M. & Silvertown, J. (2007): Prediction of extinction in plants: interactions of extrinsic threats and life history traits. *Ecology*, 88:2662–2672.

- Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M. R., Sharifi, A., Smith, P. & Yamagata, Y. (2014): Betting on negative emissions. *Nature Clim. Change*, 4: 850–853.

- Gascon, C., Collins, J. P., Moore, R. D., Church, D. R., McKay, J. E. & Mendelson, J. R. III (eds) (2007). *Amphibian Conservation Action Plan*.

IUCN/SSC Amphibian Specialist Group. Gland, Switzerland and Cambridge, UK. 68pp.

- Gerland, P., Raftery, A. E., Seveikova, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B. K., Chunn, J., Lalic, N., Bay, G., Buettner, T., Heilig, G. K.& Wilmoth, J. (2014): World population stabilization unlikely this century. *Science,* 346(6206): 234-237.

- Giddy, C. (1974): Cycads of South Africa. *Purnell and Sons* (S.A.) (Pty) Ltd, Cape Town, South Africa.

- Giddy, C. (1984): Cycads of South Africa. Second edition. C. Struik (Pty) Ltd. Publishers, Cape Town.

- Goèl, A. K. & Khuraijam, J. S. (2015): Cycads: An Overview. In: Bahadur, B., Sahijram, M. V. R. L. & Krishnamurthy, K. V. (Eds): *Plant Biology and Biotechnology: Plant Diversity, Organization, Function and Improvement*.*Uttar Pradesh, India*, Springer, 1: 349-360. DOI 10.1007/978-81-322-2286-6_10.

- Golding, J. S. & Hurter, P. J. H. (2003): A Red List account of Africa's cycads and implications of considering life-history and threats. *Biodiversity and Conservation,* 12: 507-528.

- Goode, D. (1989): Cycads of Africa. Striuk Winchester.

- Grace, J. B. & Pugesek, B. H. (1997): A structural equation model of plant species richness and its application to a coastal wetland. *Am. Nat*. 149: 436 – 460.

- Grace, J. B. & Pugesek, B. H. (1998): On the use of path analysis and related procedures for the investigation of ecological problems. *Am. Nat.* 152: 151 – 159.

- Grace, J. B. (2006): *Strucutral EquationModeling and Natural Systems*. CambridgeUniversity Press, NewYork, NY.

- Grace, J.B., Michael Anderson, T., Smith, M.D., Seabloom, E., Andelman, S.J.&Meche, G. (2007): Does species diversity limit productivity in natural grassland communities? *Ecology Letters*, 10: 680–689.

- Grace, J.B., Schoolmaster, D. R. Jr., Guntenspergen, G. R., Little, A. M., Mitchell, B. R., Miller, K. M. & Schweiger, E. W. (2012): Guidelines for a graph-theoretic implementation of structural equation modeling. *Ecosphere*, 3(8), 73. http://dx.doi.org/10.1890/ES12-00048.1.

- Grace, J. B., Scheiner, S. M. & Schoolmaster, D. R. (2015): Structural equation modeling: building and evaluating causal models. *Ecological Statistics*: *From Principles to Applications* (eds) G. A. Fox, S. Negrete-Yanlelevich & V. J. Sosa, pp. 168–199. *Oxford University Press*, NewYork, NY.

- Grandcolas, P., Nattier, R., Legendre, F. &Pellens, R. (2011): Mappingextrinsic traits such as extinction risks or modelled bioclimatic niches on phylogenies: Does it make sense at all? *Cladistics,* 27: 181–185.

- Gülez, S., (1992): A method for evaluating areas for national park status. *Environmental Management*, 16(6): 811-818.

- Harberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W. & Fische-Kowalski, M. (2007): Quantifying and mapping the human appropriation of net primary production in Earth's ecosystem. *Proceeding of the National Academy of Sciences of the United States of America*, 104: 12942-12947.

- Harmic, J. L. (2004): Response of forest trees to global environment. *Forest Ecology and Management,* 197: 323-335.

- Haynes, J. L. (2011): The world list of cycads: A historical view. IUCN/ SSC Cycad Specialist Group, 37 pp. <htpp://cycadsg.org/publications/Haynes-Historical-Review-of-World-List-of-Cycads-2011.pdf>

- Hayward, P. & Kuwahara, S. (2012): Sosetsu heritage-cycads, sustenance and cultural landscapes in Amami Islands. *The Australasian-Pacific Journal of Regional Food Studies*, 2: 26-46.

- Hendricks, J. G. (1987): The Gondwanan*Cycas*. *Encephalartos,* 10: 24–25.

- Hermsen, E. J., Taylor, T. N., Taylor, E. L. & Stevenson, D. W. (2006): Cataphylls of the middle Triassic cycad *Antarcticycas schopfii* and the new insights into cycad evolution. *American Journal of Botany*, 93: 724-738.

- Hermsen, E. J., Taylor, E. L. &Taylor, T. N. (2009): Morphology and ecology of the *Antarcticycas* plant. *Review of Palaeobotany and Palynology*, 153:108–123.

- Hill, K.D., Chase, M. W., Stevenson, H. G. & Schutzman, B. (2003): The families and genera of cycads: A molecular phylogenetic analysis of Cycadophyta based on nuclear and plastid DNA sequences. *International Journal of Plant Sciences*, 164: 933-948.

- Hill, K. D., Dennis, W. S. & Osborne, R. (2004): The World List of Cycads. IUCN/SSC Cycad Specialist Group.

- Hill, K. D. (2004): Character evolution, species recognition and classification concepts in the Cycadaceae. In T. Walters, & R. Osborne (Eds.), *Cycad* *classification, concepts and recommendations (23–44). Wallingford*: CABI Publishing.

- Hill, K. D., Stevenson, D. W. & Osborne, R. (2007): The world list of cycads. Proceedings of the seventh International Conference on Cycad Biology. *Memoirs of New York Botanical Garden,* 97: 454-483.
- Howard, S. D. & Bickford, D. P. (2014): Amphibians over the edge: silent extinction risk of data-deficient species. *Divers. Distrib*, 20:837–846.
- Iriondo, J. M., Albert, M. J. & Escudera, A. (2003): Structural equation modeling: an alternative for assessing causal relationships in threatened plant populations. *Biology Conservation*, 113: 367-377.
- Isaac, N. J., Turvey, S. T., Collen, B., Waterman, C. & Baillie, J. E. (2007): Mammals on the EDGE: Conservation priorities based on threat and phylogeny. *PLoS ONE*, 2: e296.
- Isaac, N. J. B., Redding, D. W., Meredith, H. M. & Safi, K. (2012): Phylogenetically Informed Priorities for Amphibian Conservation. *PLoS ONE*, 78: e43912.
- IUCN (2010a): IUCN Red List Categories and Criteria. Version 3.1. http://www.iucn.org/about/work/programmes/species/red_list/.
- Jetz, W., Rahbek, C. & Colwell, R. K. (2004): The coincidence of rarity and richness and the potential signature of history in centres of endemism. *Ecology Letters,* 7: 1180-1191.
- Jetz, W., Thomas, G. H., Joy, J. B., Hartmann, K. & Mooers, A. O. (2012): The global diversity of birds in space and time. *Nature*, 491: 444–448.

- Jetz, W., Thomas, G. H., Joy, J. B., Redding, D. W., Hartmann, K. & Mooers, A. O. (2014). Global distribution and conservation of evolutionary distinctness in birds. *Current Biology*, 24: 919–930.

- Jones, D. L. (2002): Cycads of the World, ancient plants today is landscape. Second edition. *New Holland Publishers*, Australia.

- Jones, D. L. (1993): Cycads of the World: Ancient Plants in Today's Landscape. REED (William Heinemann). *Chatswood*, Australia.

- Kannan, R & James, D. A. (2009): Effects of climate change on global biodiversity: A review of key literature. *Tropical Ecology,* 50(1): 31-39.

- Kembel, S. V., Cowan, P. D., Helmus, M. R., Cornwell, W. K., Morlon, H. (2010): Picante: R tools for integrating phylogenies and ecology. *Bioinformatics*, 26: 1463-1464.

- Khuraijam, J. S. & Roy, R. K. (2016): Indian *Cycas* under severe threat. *Current Science*, 111: 1756-1758.

- Krishnamurthy, V., Mandle, L. Ticktin, T., Ganesan, R., Saneesh, C. S. & Varghese, A. (2013): Conservation status and effects of harvest on an endemic multi-purpose cycad, *Cycas circinalis* L., Western Ghats, India. *Tropical Ecology,* 54(3): 309–320.

- La Peyre, M. K., Mendelssohn, I. A., Templet, P. H. &Grace, J. B. (2001): Identifying determinants of nations' wetland management programs using structural equation modeling: an exploratory analysis. *Environ. Manage*. 27: 859-868.

- Lawler, J. J., Shafer, S. L., White, D., Kareiva, P., Maurer, E. P., Blaustein, A. R. & Bartlein, P. (2009): Projected climate-induced faunal change in the Western Hemisphere. *Ecology,* 90: 588–597.

- Leao, T. C. C., Fonseca, C. R., Peres, C. A. &Tabarelli, M. (2014): Predicting extinction risk of Brazilian Atlantic Forest Angiosperms. *Conservation Biology*, 28: 1349–1359.

- Lefcheck, J.S. (2016): PIECEWISESEM: Piecewise structural equation modelling in R for ecology, evolution, and systematics. *Methods in Ecology and Evolution,* 7: 573–579.

- Lindström, A. J. (2009): Typification of some species names in *Zamia L*. (Zamiaceae), with an assessment of the status of *Chigua* D.W. Stev.*Taxon*, 58: 265–270.

- Luiz, O. J. Woods, R. M. Madin, E. M. P. &Madin, J. S. (2016): Predicting IUCN extinction risk categories for the world's data deficient groupers (Teleostei:Epinephelidae). *Conservation Letters*, 9: 342–350.

- Lung, T., Meller, L., van Teeffelen, A. J. A., Thuiller, W. & Cabeza, M. (2014): Biodiversity funds and conservation needs in the EU under climate change. *Conservation Letters.*

- Luo, W. H., Tang, W. X., Huang, S. X., Liang, H. L., & Zhao, B. (2014): Ex situ conservation of *Cycasdebaoensis*: A rare and endangered plant. *Journal of Zhejiang A & F University*, 31: 812–816.

- Mace, G. M., Gittleman, J. L. & Purvis.A. (2003): Preservingthe tree of life. *Science,* 300: 1707–1709.

- Malaeb, Z. A., Summers, J. K. & Pugesek, B. H. (2000): Using structural equation modeling to investigate relationships among ecological variables. *Environ. Ecol. Stat*. 7: 93-111.

- Magurran, A. & Dornelas, M. (2010): Introduction: biological diversity in a changing world. *Philos. Trans. R. Soc. B,* 365: 3593–3597.

- Mankga, L, T. & Yessoufou, K. (2017): Factors driving the global decline of cycad diversity. *AoB PLANTS,* 9: plx022.

- Marler, P. N. & Marler, T. E. (2015): An assessment of Red List data for the Cycadales. *Tropical Conservation Science*, 8(4): 1114-1125.

- McLellan, R., Iyengar, L., Jeffries, B.& Oerlemans, N. (Eds.), (2014): Living Planet Report 2014: Species and Spaces, People and Places. *World Wildlife Fund*, Washington, DC.

- Millennium Ecosystem Assessment (2005): Ecosystems and human well-being: synthesis. Island Press, Washington, DC, 137.

- Miller. T. G. & Spoolman, S. (2017): Environmental Science: Sustaining your World. *National Geographic Learning* **|** *Cengage Learning1 N*. State Street, Suite 900 Chicago, IL 60602. ISBN: 9781305637429.

- Mooers, A. Ø. Faith, D. P. &Maddison, W. P. (2008): Converting endangered species categories to probabilities of extinction for phylogenetic conservation prioritization. *PLoSONE*, 3: e3700.

- Mooers, A., Gascuel, O., Stadler, T., Li, H. &Steel, M. (2012): Branch lengths on birth–death trees and the expected loss of phylogenetic diversity. *Systematic Biology*, 61: 195–203.

- Mugasha, W. A., Bollandsa˚s, O. M. &Eid, T. (2013): Relationshipsbetweendiameter and height of trees in natural tropical forest in Tanzania. *Southern Forests*, 75: 221–237.

- Myers, N., Mittermeirs, R. A., da Fonseca, G. A. B. & Kent, J. (2000): Biodiversity hotspots for conservation priorities. *Nature,* 403 (6772): 853-858.

- Nagalingum, N.S., Marshall, C.R., Quental, T. B., Rai, H. S., Little, D. P. & Matthews, S. (2011): Recent synchronous radiation of a living fossil. *Science* 334: 796–799.

- Niklas, K. J. (1997). The evolutionary biology of plants. Univ. of Chicago Press, Chicago, IL.

- Norstog, K. J. & Nicholls, T. J. (1997): The biology of the cycads. Ithaca, New York: CornellUniversity Press.

- Nylander, J. A. A. (2004): Modeltest v2. Program distributed by the author. Sweden: *Evolutionary Biology Centre*, Uppsala University.

- Okubamichael, D. Y., Jack, S. L., Bösenberg, J. D. Hoffman, M. T. & Donaldson, J. S. (2016): Repeat photography confirms alarming decline in South African cycads. *Biodiversity Conservation,* 25(11): 2153–2170.

- Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., Damico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnut, T. F., Rickets, T. H., Kura, Y., Lamoreux, J. F., Hedao, P. & Kassein, K. R. (2001): Terrestrial ecoregions of the worlds: A new map of life on Earth.*Bioscience*, 51: 933-938.

- Orme, C. D. L, Davies, R. G., Burgess, M., Eigenbrod, F., Pickup, N., Olson, V. A., Webster, A. J., Ding, T-S., Rasmussen, P. C., Ridgely, R. S., Stattersfield, A. J., Bennett, P. M., Blackburn, T. M., Gaston, K. J. & Owens, I. P. F. (2005): Global hotspots of species richness are not congruent with endemism or threat. *Nature,* 436: 1016–1019.

- Osborne, R. & Hendricks, J. (1985): A world list of cycads. *Encephalartos*, 3: 13-17.

- Osborne, R., Grove, A., Oh, P., Mabry, T. J., Ng, J. C. &. Seawright, A. A (1994): The magical and medicinal usage of *Stangeria eriopus* in South Africa. *Journal of Ethnopharmacology,* 43: 67–72.

- Osborne, R., Calonje, M.A., Hill, K.D., Stanberg, L. & Stevenson, D. W. (2012): The world list of Cycads. *Memoirs of the New York Botanical Garden*, 106: 480–510.

- Owen, N. (2014): Life on the edge. *Significance*, 11: 26-29.

- Pearson, H. H. W. (1905): Notes on South African cycads. *Transactions of the South African Philosophical Society,* 16: 341–354.

- Pellens, R. & Grandcolas, P. (2016): Biodiversity conservation and phylogenetic systematics: preserving our evolutionary heritage in an extinction crisis. Switzerland: *Springer International Publishing*, AG.

- Pievani, T. (2014): The sixth mass extinction: Anthropocene and the human impact on Biodiversity. *Rend. Fis. Acc. Lincei*, 25: 85-93.

- Pot, C., McLoughlin, S. & Lindström, A. (2010): Late Paleozoic foliage from China displays affinities to Cycadales rather than to Bennettitales necessitating reevaluation of the Paleozoic Pterophyllum species. *Acta Paleontologica*, 55: 157-168.

- Prantner, B. (2011): Visualization of imputed values using the R-package VIM. http://cran.r-project.org/web/packages/VIMGUI/vignettes/VIM-Imputation.pdf

- Pullaiah, T., Bahadur, B. & Krishnamurthy, K. V. (2015): Plant Biodiversity. In: Bahadur, B., Sahijram, M. V. R. L. & Krishnamurthy, K. V. (eds): *Plant Biology and Biotechnology: Plant Diversity, Organization, Function and Improvement*.*Uttar Pradesh, India*, Springer, 1: 177-195.

- Pulido, M. T., Vargas-Zenteno, M., Vite, A. & Vovides, A, P (2015): Range extension of the endangered Mexican cycad *Ceratozamia fuscoviridis* Moore (teosintle): implications for conservation. *Tropical Conservation Science,* 8(3): 778-795.

- Purvis, A. (2008): Phylogenetic approaches to the study of extinction. *Annual Review of Ecology and Systematics*, 39: 301–319.

- Purvis, A., Agapow, P. M., Gittleman, J. L. & Mace, G. M. (2000):Non-random extinction and the loss of evolutionary history. *Science*, 288: 328–330.

- Qian, H., Wiens, J.J., Zhang, J. & Zhang, Y. (2015): Evolutionary and ecological causes of species richness patterns in North American angiosperm trees. *Ecography,* 38: 241–250.

- Radha, P. & Singh. R. (2008): Ethnobotany and conservation status of Indian *Cycas* species. *Encephalartos,* 93(1): 15–21.

- R Core Team. (2015): R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

- Rai, H. S., Osbrien, H. E., Reeves, P. A., Olmstead, R. G. & Graham, S. W. (2003): Inference of higher-order relationships in the cycads from a large chloroplast data set. *Molecular Phylogenetics and Evolution*, 29: 350-359.

- Raimondo, D. C. & Donaldson, J. S. (2003): Responses of cycads with different life histories to the impact of plant collecting: simulation models to determine important life history stages and population recovery times. *Biological Conservation,* 111: 345-358.

- Rambaut, A.& Drummond, A.J. (2007): TreeAnnotator (version 1.5.4).Retrieved from http://beast.bio.ed.ac.uk.

- Ran, J. H., Wang, P. P., Zhao, H. J. & Wang, X. Q. (2010): A test of seven candidate barcode regions from the plastome in *Picea* (Pinaceae). *Journal of Integrative Plant Biology,* 52: 1109-1126.

- Ravele, A. M. & Makhado, R. A. (2009): Exploitation of *Encephalartos transvenosus* outside and inside Mphaphuli cycads nature reserve, Limpopo Province. *South Africa. African Journal of Ecology,* 48: 105–110.

- Redding, D. W., DeWolff, C. V. & Mooers, A. O. (2010): Evolutionary distinctiveness, threat status, and ecological oddity in primates. *Conservation Biology*, 24: 1052-1058.

- Redding, D. W., Mooers, A. O., Şekercioğlu, Ç. H. & Collen, B. (2015). Global evolutionary isolation measures can capture key local conservation species in Nearctic and Neotropical bird communities. *Philosophical Transaction of the Royal Society B,* 370: 20140013.

- Retief, K. (2013): *Cycad forensics*: Tracing the origin of poached cycads using stable isotopes, trace element concentrations and radiocarbon dating techniques. *MSc dissertation, University of Cape Town*, Rondebosch, Cape Town.

- Ricketts, T. M., Dinerrstein, E., Boucher, T., Brooks, T. M., Butchart, S. E. M., Hoffmann, M., Lamoreux, J. F., Morrison, J., Par, J. D., Rodrigues, A. S. L., Sechrest, W., Wallace, G. E., Berlin, K., Bielby, J., Burgess, N . D., Church, D. R., Cox, N., Knox, D., Loucks, C., Luck, G. W., Master, L. L., Moore, R., Naidoo, R., Riggely, R., Schatz, G. E., Shire, G., Strand, H., Wettengel, W. & Wikramanayake, E. (2005): Pinpointing and preventing imminent extinctions. *Proceedings of the National Academy of Sciences of the United States of America*, 102: 18497-18501.

- Rolland, J., Condamine, F. L., Jiquet, F. & Morlon, H. (2014): Faster speciation and reduced extinction in the tropics contribute to the mammalian latitudinal diversity gradient. *PLoS Biol*, 12: e1001775.

- Salas-Leiva, D. E., Meerow, A. W., Calonjie, M., Griffith, M. P., Francisco-Ortega, J., Nakamura, K., Stevenson, D. W., Lewis, C. E. & Namoff, S. (2013): Phylogeny of the cycads based on multiple single-copy nuclear genes: congruence of concatenated parsimony, likelihood and species tree, inference methods. *Annals of Botany,* 112: 1263-1278.

- Sandel, B., Arge, L., Dalsgaard, B., Davies, R.G., Gaston, K.J., Sutherland, W.J. & Svenning, J.C. (2011): The influence of late quaternary climate change velocity on species endemism. *Science*, 334: 660–664.

- Santini, L., Saura, S. & Rondinini, C. (2016): Connectivity of the global network of protected areas. *Diversity and Distributions*, 22: 199–211.

- Schachat, S.R., Mulcahy, D.G. & Mendelson, J.R III. (2016): Conservation threats and the phylogenetic utility of IUCN Red List rankings in Incilius toads. *ConservationBiology*, 30: 72–81.

- Shipley, B. (2000): *Cause and Correlation in Biology*. A User's guide to path analysis, structural equations and causal inference. Cambridge University Press, Cambridge, UK.

- Shipley, B. (2013): The AIC model selection method applied to path analytic modelscompared using directed-separation tests. *Ecology*, 94: 560–564.

- Sodhi, N. S., Koh, L. P., Peh, K. S-H, Tan, H.T.W., Chazdon, R. L., Corlett, R. T., Lee, T. M., Cowell, R. K., Brook, B. W., Sekercioglu, C. H. & Bradshaw, C. J. A. (2008): Correlates of extinction proneness in tropical angiosperms. *Diversity and Distribution,* 14: 1–10.

- Spitale, D., Petraglia, A. & Tomaselli, M. (2009): Structural equation modeling detects unexpected differences between bryophyte and vascular plant richness along multiple environmental gradients. *Journal of Biogeography,* 36: 745–755.

- Stein, R. W., Mull, C. G., Kuhn, T. S., Aschliman, N. C., Davidson, L. N., Joy, J. B., Smith, G. J., Dulvy, N. K. & Mooers, A. O. (2018): Global priorities for conserving the evolutionary history of sharks, rays and chimaeras. *Nature Ecology and Evolution*, 2: 288.

- Stevenson, D. W. & Osborne, R. (1993a): *The world list of cycads*. Pp. 354-364 in Stevenson, D.W. & Norstog, K. (eds), Proceedings of the Second International Conference on Cycad Biology, Palm and Cycad Societies of Australia Ltd, Milton, Queensland, Australia.

- Stevenson, D. W. & Osborne, R. (1993b): The world list of cycads. *Encephalartos*, 33: 19-25.

- Stevenson, D. W. and Hill, K. D. (1995): The world list of cycads. Proceedings of the third International Conference on Cycad Biology. *Cycad Society of South Africa*, Stellenbosch, South Africa.

- Tafirei, R. (2016): An integrative approach towards setting conservation priority for cycad species at a global scale. MSc dissertation. *Department of Environmental Management, Faculty of Sciences, University of Johannesburg.*

- Taylor, T. N., Taylor, E. L. & Krings, M. (2009): Paleobotany: The Biology and Evolution of Fossil Plants. 2nd edition. Burlington: *Academic Press*.

- Taylor, A. S., Haynes, J. Z., Stevenson, D. W., Holzman, G. & Mendieta, J. (2012): *Biogeographic insights in Central American cycad biology*. Rijeka: In Tech.

- Templ, M., Alfons, A., Kowarik, A. &Prantner, B. (2016): VIM: Visualization and Imputation of Missing Values. R package version 4.6.0. https://CRAN.R-project.org/package=VIM.

- Terry, I., Forster, P. I., Moore, C. J., Roemer, R. B. & Machin, P. J. (2008): Demographics, pollination syndrome and conservation status of *Macrozamia platyrhachis* (Zamiaceae), a geographically restricted Queensland cycad. *Australian Journal of Botany*, 56: 321–332.

- Thomas, G.H., Hartmann, K., Jetz, W., Joy, J.B., Mimoto, A. & Mooers, A.O. (2013): PASTIS: An R package to facilitate phylogenetic assembly with soft taxonomic inferences. *Methods in Ecology and Evolution*, 4: 1011–1017.

- Tonini, J. F. R., Beard, K. H., Ferreira, R. B., Jetz, W. & Pyron, R. A. (2016): Fully-sampled phylogenies of squamates reveal evolutionary patterns in threat status. *Biological Conservation*, 204: 23-31.

- United Nations (2004): *World population prospects: The 2004 revision. Sex and age distributions of the world population.* The United Nations Publication.

- Urban, M. C. (2015): Accelerating extinction risk from climate change. *Science* 348 (6234): 571-573.

- Vamosi, J. C. & Vamosi, S. M. (2008): Extinction risk escalates in the tropics. *PLoS ONE,* 3: e3886.

- Vamosi, J. C. & Wilson, J. R. U. (2008): Non-random extinction leads to elevated loss of angiosperm evolutionary history. *Ecology Letters,* 11: 1047–1053.

- Vessey, J. K., Pawloski, K. & Bergman, B. (2004): Root based Nitrogen fixing symbiosis: Legumes, actinorhizal plants, *Parasponiasp* and cycads. *Plant & Soil*, 274: 51-78.

- Veron, S., Penone, C., Clergeau, P., Costa, G. C., Oliveira, B. F., Sao-Pedro, V. A. & Pavoine, S. (2016): Integrating data-deficient species in analyses of evolutionary history loss*. Ecology and Evolution,* 6: 8502–8514.

- Visconti, P., Bakkenes, M., Baisero, D., Brooks, T., Butchart, S, H. M., Joppa, L., Alkemade, R., Di Marco, M., Santini, L., Hoffmann, M., Maiorano, L., Pressey, R. L., Arponen, A., Boitani, L., Reside, A. E., van Vuuren, D. P. & Rondinini, C. (2015): Projecting Global Biodiversity Indicators under Future Development Scenarios. *Conservation Letters,* 9(1): 5-13.

- Voeks, R.A., 2004. Disturbance pharmacopoeias: medicine and myth from the humid tropics. *Annals of the Association of American Geographers*, 94(4): 868-888.

- Volis, S. (2016): How to conserve threatened Chinese plant species with extremely small populations? *Plant Diversity*, 1: 53–62.

- Vorster, P. (2004): Chapter 6: Classification concepts in *Ecncephalartos* (Zamiaceae). In Walters, T. & Osborne, R. (eds). *Cycad Classification: Concepts and recommendations.* CABI Publishing, Walligford.

- Vovides, A. P., Pérez-Farrera M. A. & Iglesias, C. (2010): Cycad propagation by rural nurseries in Mexico as an alternative conservation strategy: 20 years on. *Kew Bulletin,* 65: 603-611.

- Vredenburg, V. T., Knapp, R. A., Tunstall, T. S. & Briggs, C. J. (2010): Dynamics of an emerging disease drive large-scale amphibian population extinctions. *PNAS Ecology*, 107(21): 9689-9694.

- Wake, D.B. &Vredenburg, V.T. (2008): Are we in the midst of the sixth mass extinction? A view from the world of amphibians. *Proceedings of the Natural Academy of Sciences of the United Statesof America*, 11: 466–11473.

- Waldron, A., Mooers, A. O., Miller, D. C., Nibbelink, N., Redding, D. W., Kuhn, T. S., Roberts, J. T. & Gittleman, J. L. (2013): Targeting global conservation funding to limit immediate biodiversity declines. *Proceedings of the National Academy of Sciences of the United States of America*, 110: 12144-12148.

- Wang, D., Wu, Y. W., Shih, A. C. C., Wu, C. S., Wang, Y. N. & Chaw, S. M. (2007): Transfer of chloroplast genomic DNA to mitochondrial genome occurred at least 300 Mya. *Molecular Biology and Evolution,* 24: 2040-2048.

- Warren, W. C., Hillier, L. W., Graves, J. A. M., Birney, E., onting, C. P., Grützner, F., Belov, K., Miller, W., Clarke, L., Chinwalla, A. T & Yang, S. P. (2008): Genome analysis of the platypus reveals unique signatures of evolution. *Nature*, 453: 175-183.

- White, R.L. & Bennett, P.M. (2015): Elevational distribution and extinction risk in birds. *PLoS ONE*, 10: e0121849.

- Whitelock, L. M. (2002): *The Cycads.* Portland, OR: Timber Press. 374pp and 505 color plates. ISBN 0-88192-522-5.

- Whittaker, R. J., Araujo, M. B., Paul, J., Ladle, R. J., Watson, J. E. M. & Willis, K. J. (2005): Conservation Biogeography: assessment and prospect. *Diversity and Distributions,* 11: 2–3.

- Willis, C. G., Ruhfel, B. R., Primack, R. B., Miller-Rushing, A. J. & Davis, C. C. (2008): Phylogenetic patterns of species loss in Thoreau's woods are driven by climate change. Proceedings of the Natural Academy of Science United States of America, 105: 17029–17033.

- Willis, C. G., Ruhfel, B. R., Primack, R. B., Miller-Rushing, A. J., Losos, J. B. & Davis, C. C. (2010): Favourable climate change response explains non-native species' success in Thoreau's Woods. *PLoS ONE,* 5: e8878.

- Wilting, H. C., Schipper, A. M., Bakkenes, M., Meijer, J. R. & Huijbregts, M. A. J. (2017): Quantifying Biodiversity Losses Due to Human Consumption: A Global-Scale Footprint Analysis. *Environ. Sci. Techn.*, 51: 3298−3306.

- Winter, M., Schweigera, O., Klotza, S., Nentwigc, W., Andriopoulosd, P., Arianoutsou, M., Basnou, C., Delipetrou, P., Didziulis, V., Hejda, M., Hulme, B. E., Lambdon, P. W., Perql, J., Pysek, P., Poy, D. B. & Kuhn, I. (2009): Plant extinctions and introductions lead to phylogenetic and taxonomic homogenization of the European flora. *Proceedings of the National Academy of Sciences of the United States of America*, 106: 21721-21725.

- Wright, S. J. (2005): Tropical forests in a changing environment. *Trends Ecol Evol,* 20: 553–560.
- Xiao, L-Q. & Möller, M. (2015): Nuclear Ribosomial ITS Functional Paralogs Resolve the Phylogenetic Relationships of a Late-Miocene Radiation Cycad *Cycas* (Cycadaceae), *Plos One*, 10: e0117971.
- Xiao-fu, X., Jian, S., Hong-tao., N., De-kui, Y. & Jian-hua., T. (2016): Linking Structural Equation Modeling with Bayesian Network and Its Application to Coastal Phytoplankton Dynamics in the Bohai Bay. *China Ocean Eng*., 30(5): 733 – 748.
- Yessoufou, K., Daru, B. H. & Davies, T. J. (2012): Phylogenetic patterns of extinction risk in the Eastern arc ecosystem an African biodiversity hotspot. *PLoSONE*, 7: e47082.
- Yessoufou, K., Bamigboye, S. O, Daru, B. H. & van der Bank, M. (2014): Evidence of constant diversification punctuated by a mass extinction in the African cycads. *Ecology and Evolution*, 4: 50–58.
- Yessoufou, K. & Davies, T.J. (2016): Re-considering the loss of evolutionary history: how does non-random extinction prune the tree of life? In: Pellens R, Grandcolas P, eds. *Biodiversity conservation and phylogenetic systematics*.14: 57–80.
- Yessoufou, K., Daru, B. H., Tafirei, R., Elansary, H. O. &Rampedi, I. (2017): Integrating biogeography, threat and evolutionary data to explore extinction crisis in the taxonomic group of cycads. *Ecology and Evolution*, 7: 2735–2746.

- Zheng, Y., Liu, J., Feng, X. & Gong, X. (2017): The distribution, diversity, and conservation status of *Cycas* in China. *Ecol Evol*, 7: 3212–3224.

- Zonneveld & Lindström, (2016): Genome sizes for 71 species of *Zamia* (Cycadales: *Zamiaceae*) correspond with three different biogeographic regions. *Nordic Journal of Botany,* 000: 001–008.

- Zgurski, J. M., Rai, H. S., Bogler, D. J., Francisco-Ortega, J. & Graham, S. W. (2008): How well do we understand the overall backbone of cycad ohylogeny? New insights from a large, multigene plastid data set. *Molecular Phylogenetics and Evolution*, 47: 1232-1237.

APPENDIX

Appendix1: Acompiled world list of cycad taxa, their global distributionand the threat status (Threatened vs. non-threatened).

Nº	Species	Location	Threat status
1.	*Bowenia serrulata*	Australia (Queensland)	Non-threatened
2.	*Bowenia spectabilis*	Australia (Queensland)	Non-threatened
3.	*Ceratozamia alvarezii*	Mexico (Chiapas)	Threatened
4.	*Ceratozamia becerrae*	Mexico (Chiapas, Tabasco)	Threatened
5.	*Ceratozamia brevifrons*	Mexico (Veracruz)	Threatened
6.	*Ceratozamia chimalapensis*	Mexico (Oaxaca)	Threatened
7.	*Ceratozamia decumbens*	Mexico (Veracruz)	Threatened
8.	*Ceratozamia euryphyllidia*	Mexico (Oaxaca, Veracruz)	Threatened
9.	*Ceratozamia fuscoviridis*	Mexico (Hidalgo, Veracruz)	Threatened
10.	*Ceratozamia hildae*	Mexico (Querétaro, San Luis Potosí)	Threatened

11.	*Ceratozamia hondurensis*	Mexico (Chiapas)	Threatened
12.	*Ceratozamia huastercorum*	Mexico (Veracruz)	Threatened
13.	*Ceratozamia latifolia*	Mexico (Hidalgo, Querétaro, San Luis Potosí, Veracruz)	Threatened
14.	*Ceratozamia matudae*	Guatemala (Huehuetenango, San Marcos), Mexico (Chiapas)	Threatened
15.	*Ceratozamia mixeorum*	Guatemala, Mexico (Chiapas)	Threatened
16.	*Ceratozamia mexicana*	Mexico (Puebla, Veracruz)	Threatened
17.	*Ceratozamia microstrobila*	Mexico (San Luis Potosí)	Threatened
18.	*Ceratozamia miqueliana*	Mexico (Chiapas, Tabasco, Veracruz)	Threatened
19.	*Ceratozamia mirandae*	Mexico (Chiapas)	Threatened
20.	*Ceratozamia morettii*	Mexico (Veracruz)	Threatened
21.	*Ceratozamia norstogii*	Mexico (Chiapas, Oaxaca)	Threatened
22.	*Ceratozamia robusta*	Belize (Cayo, Stann Creek, Toledo), Guatemala (Alta Verapaz, Petén, Quiché, Huehuetenango, Izabal), Mexico	Threatened

		(Chiapas, Oaxaca, Veracruz)	
23.	*Ceratozamia sabatoi*	Mexico (Hidalgo, Queretaro)	Threatened
24.	*Ceratozamia santillanii*	Mexico (Chiapas)	Threatened
25.	*Ceratozamia vovidesii*	Mexico (Chiapas)	Threatened
26.	*Ceratozamia whitelockiana*	Mexico (Oaxaca)	Threatened
27.	*Ceratozamia zaragozae*	Mexico (San Luis Potosí)	Threatened
28.	*Ceratozamia zoquorum*	Mexico (Chiapas)	Threatened
29.	*Chigua bernalii*	Colombia (Cordoba)	Threatened
90.	*Cycas aculeate*	Vietnam (Da Nang)	Threatened
31.	*Cycas aenigma*	Philippines (Palawan-cult.)	Threatened
32.	*Cycas angulata*	Australia (Northern Territory and Queensland)	Non-threatened
33.	*Cycas anhemica*	Australia (Northern Territory)	Non-threatened
34.	*Cycas annaikalensis*	India (Western Ghats)	Threatened
35.	*Cycas apoa*	Indonesia (Papua), Papua New Guinea (West Sepik, Morobe)	Non-threatened

36.	*Cycas arenicola*	Australia (Northern Territory)	Non-threatened
37.	*Cycas armstrongii*	Australia (Northern Territory)	Threatened
38.	*Cycas badensis*	Australia (Queensland)	Non-threatened
39.	*Cycas balansae*	China (Guangxi), Vietnam (Lang Son, QuangNinh, Thai Nguyen, VinhPhuc)	Non-threatened
40.	*Cycas basaltca*	Australia (Western Australia)	Non-threatened
41.	*Cycas beddomei*	India (Andhra Pradesh)	Threatened
42.	*Cycas bifida*	China (Guangxi, Yunnan), Vietnam (Cao Bang, Lang Son, TuyenQuang)	Threatened
43.	*Cycas bougainvilleana*	Papua New Guinea (Bougainville, New Britain), Solomon Islands	Non-threatened
44.	*Cycas brachycantha*	Vietnam (Bac Kan)	Non-threatened
45.	*Cycas brunnea*	Australia (Northern Territory, Queensland)	Non-threatened
46.	*Cycas cairnsiana*	Australia (Queensland)	Threatened
47.	*Cycas calcicola*	Australia (Northern Territory)	Non-threatened
48.	*Cycas campestris*	Papua New Guinea (Central, Gulf)	Non-threatened
49.	*Cycas canalis*	Australia (Northern Territory)	Non-threatened
50.	*Cycas candida*	Australia (Northern Territory)	Threatened

51.	*Cycas cantafolia*	Malaysia (Johor)	Threatened
52.	*Cycas chamaoensis*	Thailand (Chantaburi)	Threatened
53.	*Cycas chamberlainii*	Philippines (Luzon)	Threatened
54.	*Cycas changjiangensis*	China (Hainan)	Threatened
55.	*Cycas chevalieri*	Vietnam (Ha Tinh, Nghe An, QuangBinh, Quang Tri)	Non-threatened
56.	*Cycas circinalis*	India (Andra Pradesh, Karnataka, Kerala, Maharashtra Tamil Nadu)	Threatened
57.	*Cycas clivicola*	Malaysia (Kedah, Perak, Selangor), Thailand (Chumphon, Narathiwat, PhangNga, Phuket, Ranong, Trang)	Non-threatened
58.	*Cycas collina*	Vietnam (Son La)	Threatened
59.	*Cycas condaoensis*	Vietnam (Ba Ria-Vung Tau)	Threatened
60.	*Cycas conferta*	Australia (Northern Territory)	Non-threatened
61.	*Cycas couttsiana*	Australia (Queensland)	Non-threatened
62.	*Cycas cupida*	Australia (Queensland)	Threatened
63.	*Cycas curranii*	Philippines (Palawan)	Threatened

64.	*Cycas debaoensis*	China (Guangxi)	Threatened
65.	*Cycas desolata*	Australia (Queensland)	Threatened
66.	*Cycas diannanensis*	China (Yunnan), North Vietnam	Threatened
67.	*Cycas dolichphylla*	China (Yunnan), Vietnam (Bac Kan, Cao Bang, Ha Giang, Lai Chau, Lao Cai, NinhBinh, Son La, Thai Nguyen, ThanhHoa, TuyenQuang)	Non-threatened
68.	*Cycas edentate*	Indonesia (Bali, Bengkulu, Jawa Barat, Jawa Tengah, JawaTimur, Lampung, Riau, Sumatra Utara), Malaysia (Johore, Langkawi, Malacca, Pahang, Perak, Sabah, Sarawak, Terengganu), Myanmar, Philippines (Balabac, Basilan, Cebu, Masbate, Mindanao, Mindoro, Negros, Palawan, Panay, Polillo), Singapore (Changi), Thailand (Chumphon, Narathiwat, PhangNga, PhuKet, Satun, Trang, Trat), Vietnam (KienGiang)	Non-threatened
69.	*Cycas elephantipes*	Thailand (Chaiyaphum)	Threatened
70.	*Cycas elongate*	Vietnam (BinhDinh, KhanhHoa, NinhThuan, Phu Yen, Quang Ngai)	Threatened

71.	*Cycas falcata*	Indonesia (Sulawesi Selatan, Sulawesi Tenggara)	Threatened
72.	*Cycas ferruginea*	China (Guangxi), Vietnam (Lang Son, Thai Nguyen)	Non-threatened
73.	*Cycas fugax*	Vietnam (PhuTho)	Threatened
74.	*Cycas guizhouensis*	China (Guangxi, Guizhou, Yunnan)	Threatened
75.	*Cycas hainanensis*	China (Hainan)	Threatened
76.	*Cycas hoabinhensis*	Vietnam (Ha Nam, Ha Tay, HoaBinh, NinhBinh)	Threatened
77.	*Cycas hongheensis*	China (Yunnan)	Threatened
78.	*Cycas indica A.*	India (Karnataka)	Threatened
79.	*Cycas inermis*	Vietnam (Da Nang, Dong Nai, KhanhHoa, Quang Nam)	Threatened
80.	*Cycas javana*	Indonesia (Jawa Barat, Jawa Tengah, JawaTimur)	Threatened
81.	*Cycas kuesteriana*	Vietnam (Da Nang, Dong Nai, KhanhHoa, Quang Nam)	Threatened
82.	*Cycas lacrimans*	Philippines (Mindanao)	Threatened
83.	*Cycas lane-poolei*	Australia (WA)	Non-threatened

84.	*Cycas lindstromii*	Vietnam (Ba Ria-Vung Tau, BinhThuan, KhanhHoa, NinhThuan)	Threatened
85.	*Cycas litoralis*	Indonesia (Sumatra), Malaysia, Myanmar, Thailand (Chumphon, Narathiwat, Phang Thailand (Chumphon, Narathiwat, PhangNga, Trat), Vietnam (KienGiang)	Non-threatened
86.	*Cycas maconochiei*	Australia (Northern Territory)	Non-threatened
87.	*Cycas macrocarpa*	Malaysia, Thailand (Chantaburi, Chumphon, Narathiwat, Ranong)	Threatened
88.	*Cycas media ensata*	Australia (Queensland)	Non-threatened
89.	*Cycas media media*	Australia (Queensland)	Non-threatened
90.	*Cycas megacarpa*	Australia (Queensland)	Threatened
91.	*Cycas micholitzii*	(Laos), Vietnam (Dac Lak, Gia Lai, Kon Tum)	Threatened
92.	*Cycas micronesica*	Micronesia (Mariana Islands)	Threatened
93.	*Cycas miquellii*	China, Japan (Ryukyu Islands)	Non-threatened
94.	*Cycas montana*	Indonesia (Nusa Tenggara Timur)	Non-threatened
95.	*Cycas multipinnata*	China (Yunnan), Vietnam (Yen Bai)	Threatened
96.	*Cycas nathorstii*	India (Tamil Nadu), N Sri Lanka	Threatened

97.	*Cycas nitida*	Philippines (Luzon)	Non-threatened
98.	*Cycas nongnoochiae*	Philippines (Luzon)	Threatened
99.	*Cycas ophiolitica*	Australia (Queensland)	Threatened
100.	*Cycas orientis*	Australia (Northern Territory)	Non-threatened
101.	*Cycas pachypoda*	Vietnam (BinhThuan, NinhThuan)	Threatened
102.	*Cycas panzhihuaensis*	Australia (Northern Territory)	Threatened
103.	*Cycas papuana*	Indonesia (Papua), Papua New Guinea (Western)	Non-threatened
104.	*Cycas pectinata_A*	Bangladesh, Bhutan, China (Yunnan), NE India, Laos, Myanmar, Nepal, Thailand (Chiang Mai, Kanchanaburi, Mae Hong Son, Phetchabun, Phrae, Sukhothai), Vietnam (Gia Lai, Kon Tum, Lam Dong, Quang Ngai)	Threatened
105.	*Cycas pectinata_B*	Bangladesh, Bhutan, China (Yunnan), NE India, Laos, Myanmar, Nepal, Thailand (Chiang Mai, Kanchanaburi, Mae Hong Son, Phetchabun, Phrae, Sukhothai), Vietnam (Gia Lai, Kon Tum, Lam Dong, Quang Ngai)	Threatened
106.	*Cycas petraea*	Thailand (Loei)	Non-threatened
107.	*Cycas platyphylla*	Australia (Queensland)	Threatened

108.	*Cycas pranburiensis*	Thailand (PrachuapKhiri Khan)	Threatened
109.	*Cycas pruinosa*	Australia (Northern Territory, WA)	Non-threatened
110.	*Cycas revoluta*	China, Japan (Ryukyu Islands)	Non-threatened
111.	*Cycas riuminiana*	Philippines (Luzon)	Threatened
112.	*Cycas rumphii*	Philippines (Luzon)	Non-threatened
113.	*Cycas saxatilis*	Philippines (Palawan)	Threatened
114.	*Cycas schumanniana*	Papua New Guinea (Eastern Highlands, Madang, Morobe)	Non-threatened
115.	*Cycas scratchleyana*	Indonesia (Papua, Maluku, West Papua), Papua New Guinea (Central, Gulf, Milne Bay, Western)	Non-threatened
116.	*Cycas seemani*	Australia (Torres Strait Islands), Fiji, New Caledonia, Tonga, Vanuatu	Threatened
117.	*Cycas segmentifida*	China (Guangxi, Guizhou, Yunnan), ?N Vietnam	Threatened
118.	*Cycas semota*	Australia (Queensland)	Non-threatened
119.	*Cycas sexseminifera*	China (Guangxi), Vietnam (Cao Bang, NinhBinh, ThanhHoa)	Threatened
120.	*Cycas shanyaensis*	China (Hainan Island)	Threatened

121.	*Cycas siamensis*	Cambodia, Laos, Myanmar, Thailand (Chachoengsao, Chaiyaphum, Chonburi, Kanchanaburi, Lampang, NakhonRatchasima, Phetchabun, Ratchaburi, SakonNakhon, Tak, UthaiThani, Uttaridit), Vietnam (Dac Lak, Gia Lai, Kon Tum, Nghe An, ThanhHoa)	Threatened
122.	*Cycas silvestris*	Australia (Queensland)	Threatened
123.	*Cycas simplicipinna*	Laos, Myanmar, Thailand (Chiang Mai, Loei, Mae Hong Song, Phrae), Vietnam (Quang Tri)	Non-threatened
124.	*Cycas sphaerica*	India (Andaman and Nicobar Islands), S Sri Lanka	Threatened
125.	*Cycas sundaica*	Indonesia (Nusa Tenggara Timur)	Non-threatened
126.	*Cycas szechuanensis*	China (Fujian, Guangdong)	Threatened
127.	*Cycas taitungensis*	China (Taiwan)	Threatened
128.	*Cycas taiwaniana*	China (Guangdong)	Threatened
129.	*Cycas tanqingii*	China (Yunnan), ?Vietnam (Lai Chau)	Non-threatened
130.	*Cycas tansachana*	Thailand (Saraburi)	Threatened

131.	*Cycas terryana*	Australia (Queensland)	Threatened
132.	*Cycas thouarsii*	Comoros, Kenya, Madagascar, Mozambique, Seychelles, Tanzania	Non-threatened
133.	*Cycas tropophylla*	Vietnam (Hai Phong, QuangNinh)	Non-threatened
134.	*Cycas tuckeri*	Australia (Queensland)	Threatened
135.	*Cycas vespertilio*	Philippines (Cebu, Leyte, Luzon, Negros, Panay, Samar)	Non-threatened
136.	*Cycas wadei*	Philippines (Culion)	Threatened
137.	*Cycas xipholepis*	Australia (Queensland)	Non-threatened
138.	*Cycas yorkiana*	Australia (Queensland)	Non-threatened
139.	*Cycas zambalensis*	Philippines (Luzon)	Threatened
140.	*Cycas zeylanica*	India (Andaman and Nicobar Islands), Sri Lanka	Threatened
141.	*Dioon angustifolium*	Mexico (Nuevo León, Tamaulipas)	Threatened
142.	*Dioon argenteum*	Mexico (Oaxaca)	Threatened
143.	*Dioon califanoi*	Mexico (Oaxaca, Puebla)	Threatened

144.	*Dioon caputoi*	Mexico (Oaxaca, Puebla)	Threatened
145.	*Dioon edule*	Mexico (Hidalgo, Querétaro, San Luis Potosí, Tamaulipas, Veracruz)	Non-threatened
146.	*Dioon holmgrenii*	Mexico (Oaxaca)	Threatened
147.	*Dioon mejiae*	Honduras (Colón, Olancho, Yoro)	Non-threatened
148.	*Dioon merolae*	Mexico (Chiapas, Oaxaca)	Threatened
149.	*Dioon purpusii*	Mexico (Oaxaca)	Threatened
150.	*Dioon rzedowskii*	Mexico (Oaxaca)	Threatened
151.	*Dioon sonorense*	Mexico (Sinaloa, Sonora)	Threatened
152.	*Dioon spinulosum*	Mexico (Oaxaca, Veracruz)	Threatened
153.	*Dioon stevensonii*	Mexico (Guerrero, Michoacán)	Threatened
154.	*Dioon tomasellii*	Mexico (Durango, Jalisco, Nayarit)	Threatened
155.	*Encephalartos aemulans*	South Africa (KwaZulu-Natal)	Threatened
156.	*Encephalartos altensteinii*	South Africa (Eastern Cape)	Threatened

157.	*Encephalartos angustifolia*	South Africa (Eastern Cape)	Threatened
158.	*Encephalartos aplanatus*	Swaziland	Threatened
159.	*Encephalartos arenarius*	South Africa (Eastern Cape)	Threatened
160.	*Encephalartos barteri*	Benin (Bergu), Ghana, Nigeria (Plateau)	Non-threatened
161.	*Encephalartos brevifoliolatus*	South Africa (Limpopo)	EW
162.	*Encephalartos bubalinus*	Kenya (Narok), Tanzania (Arusha)	Threatened
163.	*Encephalartos caffer*	South Africa (Eastern Cape)	Threatened
164.	*Encephalartos cerinus*	South Africa (KwaZulu-Natal)	Threatened
165.	*Encephalartos chimanimaniensis*	Mozambique, Zimbabwe	Threatened
166.	*Encephalartos concinnus*	Zimbabwe (Mberemgwa, Runde)	Threatened
167.	*Encephalartos cupidus*	South Africa (Mpumalanga)	Non-threatened
168.	*Encephalartos cycadifolius*	South Africa (Eastern Cape)	Threatened
169.	*Encephalartos delucanus*	Tanzania (Mpanda)	Threatened

170.	*Encephalartos dolomiticus*	South Africa (Limpopo)	Threatened
171.	*Encephalartos dyerianus*	South Africa (Limpopo)	Threatened
172.	*Encephalartos equatorialis*	Uganda	Threatened
173.	*Encephalartos eugenemaraisii*	South Africa (Limpopo)	Non-threatened
174.	*Encephalartos ferox*	Mozambique, South Africa (KwaZulu-Natal)	non-threatened
175.	*Encephalartos fridericiguilielmi*	South Africa (Eastern Cape, KwaZulu-Natal)	Threatened
176.	*Encephalartos ghellincki*	South Africa (Eastern Cape, KwaZulu-Natal)	Threatened
177.	*Encephalartos gratus*	Malawi, Mozambique	Threatened
178.	*Encephalartos heenanii*	South Africa (Mpumalanga), Swaziland	Threatened
179.	*Encephalartos hildebrandtii*	Kenya (Kilifi, Lamu), Tanzania (Lushoto, Tanga, Zanzibar Island)	Non-threatened
180.	*Encephalartos hirsutus*	South Africa (Limpopo)	Threatened
181.	*Encephalartos horridus*	South Africa (Eastern Cape)	threatened
182.	*Encephalartos humilis*	South Africa (Mpumalanga)	threatened

183.	*Encephalartos inopinus*	South Africa (Limpopo)	threatened
184.	*Encephalartos ituriensis*	Democratic Republic of Congo (Orientale), Uganda	Non-threatened
185.	*Encephalartos kisambo*	Kenya (Taita-Taveta)	Threatened
186.	*Encephalartos laevifolius*	South Africa (Eastern Cape, KwaZulu-Natal, Limpopo, Mpumalanga), Swaziland	Threatened
187.	*Encephalartos lanatus*	South Africa (Mpumalanga)	Non-threatened
188.	*Encephalartos latifrons*	South Africa (Eastern Cape)	Threatened
189.	*Encephalartos laurentianus*	Angola, Democratic Republic of Congo	Non-threatened
190.	*Encephalartos lebomboensis*	Mozambique, South Africa (KwaZulu-Natal), Swaziland	Threatened
190.	*Encephalartos lehmannii*	South Africa (Eastern Cape)	Non-threatened
192.	*Encephalartos longifolius*	South Africa (Eastern Cape)	Non-threatened
193.	*Encephalartos mackenziei*	Sudan	Non-threatened
194.	*Encephalartos macrostrobilus*	Uganda (Northern)	Threatened
195.	*Encephalartos manikensis*	Mozambique (Manica), Zimbabwe	Threatened
196.	*Encephalartos marunguensis*	Democratic Republic of Congo (Tanganyika)	Threatened
197.	*Encephalartos middleburgensis*	South Africa (Mpumalanga)	Threatened
198.	*Encephalartos msinganus*	South Africa (KwaZulu-Natal)	Threatened
199.	*Encephalartos munchii*	Mozambique (Manica)	Threatened
200.	*Encephalartos natalensis*	South Africa (KwaZulu-Natal)	Non-threatened
201.	*Encephalartos ngoyanus*	South Africa (KwaZulu-Natal),	Threatened

		Swaziland	
202.	*Encephalartos nubimontanus*	South Africa (Limpopo)	EW
203.	*Encephalartos paucidentatis*	South Africa (Mpumalanga), Swaziland	Threatened
204.	*Encephalartos poggei*	Democratic Republic of Congo (Lulua, Lomami, Lualaba)	Non-threatened
205.	*Encephalartos princeps*	South Africa (Eastern Cape)	Threatened
206.	*Encephalartos pterogononus*	Mozambique (Manica)	Threatened
207.	*Encephalartos relictus*	Swaziland	EW
208.	*Encephalartos schaijesii*	Democratic Republic of Congo (Lualaba)	Threatened
209.	*Encephalartos schmitzii*	Democratic Republic of Congo (Haut -Katanga), Zambia	Threatened
210.	*Encephalartos sclavoi*	Tanzania (Tanga)	Threatened
211.	*Encephalartos senticosus*	South Africa (KwaZulu-Natal), Swaziland	Threatened
212.	*Encephalartos septentrionalis*	Sudan, Uganda	Non-threatened
213.	*Encephalartos tegulaneus*	Kenya	Non-threatened
214.	*Encephalartos transvenosus*	South Africa (Limpopo)	Non-threatened
215.	*Encephalartos trispinosus*	South Africa (Eastern Cape)	Threatened
216.	*Encephalartos turneri*	Mozambique (Nampula)	Non-threatened
217.	*Encephalartos umbeluziensis*	Mozambique, Swaziland	Threatened
218.	*Encephalartos villosus*	South Africa (Eastern Cape, KwaZulu-Natal), Swaziland	Non-threatened
219.	*Encephalartos whitelockii*	Uganda	Threatened
220.	*Encephalartos woodii*	South Africa (KwaZulu-Natal)	EW
221.	*Lepidozamia hopei*	Australia (Queensland)	Non-threatened

222.	*Lepidozamia peroffskyana*	Australia (New South Wales, Queensland)	Non-threatened
223.	*Macrozamia cardiacensis*	Australia (Queensland)	Threatened
224.	*Macrozamia communis*	Australia (New South Wales)	Non-threatened
225.	*Macrozamia concinna*	Australia (New South Wales)	Non-threatened
226.	*Macrozamia conferta*	Australia (Queensland)	Threatened
227.	*Macrozamia cranei*	Australia (Queensland)	Threatened
228.	*Macrozamia crassifolia*	Australia (Queensland)	Threatened
229.	*Macrozamia diplomera*	Australia (New South Wales)	Non-threatened
230.	*Macrozamia douglasii*	Australia (Queensland)	Non-threatened
231.	*Macrozamia dyeri*	Australia (Western Australia)	Non-threatened
232.	*Macrozamia elegans*	Australia (New South Wales)	Threatened
233.	*Macrozamia fawcettii*	Australia (New South Wales)	Non-threatened
234.	*Macrozamia fearnsidei*	Australia (Queensland)	Non-threatened
235.	*Macrozamia flexuosa*	Australia (New South Wales)	Threatened
236.	*Macrozamia fraseri*	Australia (Western Australia)	Non-threatened
237.	*Macrozamia glaucophylla*	Australia (New South Wales)	Non-threatened
238.	*Macrozamia heteromera*	Australia (New South Wales)	Non-threatened
239.	*Macrozamia humilis*	Australia (New South Wales)	Threatened
240.	*Macrozamia johnsonii*	Australia (New South Wales)	Non-threatened
241.	*Macrozamia lomandroides*	Australia (Queensland)	Threatened
242.	*Macrozamia longispina*	Australia (Queensland)	Non-threatened
243.	*Macrozamia lucida*	Australia (New South Wales, Queensland)	Non-threatened
244.	*Macrozamia macdonnelli*	Australia (Northern Territory)	Non-threatened

245.	*Macrozamia machinii*	Australia (Queensland)	Threatened
246.	*Macrozamia macleayi*	Australia (Queensland)	Non-threatened
247.	*Macrozamia miquelii*	Australia (Queensland)	Non-threatened
248.	*Macrozamia montana*	Australia (Northern Territory)	Non-threatened
249.	*Macrozamia moorei*	Australia (Queensland)	Non-threatened
250.	*Macrozamia mountperriensis*	Australia (Queensland)	Non-threatened
251.	*Macrozamia occidua*	Australia (Queensland)	Threatened
252.	*Macrozamia parcifolia*	Australia (Queensland)	Threatened
253.	*Macrozamia pauliguilielmi*	Australia (Queensland)	Threatened
254.	*Macrozamia platyrhachis*	Australia (Queensland)	Threatened
255.	*Macrozamia plurinervia*	Australia (North South Wales)	Threatened
256.	*Macrozamia polymorpha*	Australia (New South Wales)	Non-threatened
257.	*Macrozamia reducta*	Australia (New South Wales)	Non-threatened
258.	*Macrozamia reidlei*	Australia (Western Australia)	Non-threatened
259.	*Macrozamia secunda*	Australia (New South Wales)	Threatened
260.	*Macrozamia serpentine*	Australia (Queensland)	Non-threatened
261.	*Macrozamia spiralis*	Australia (New South Wales)	Threatened
262.	*Macrozamia stenomera*	Australia (New South Wales)	Non-threatened
263.	*Macrozamia viridis*	Australia (New South Wales)	Threatened
264.	*Microcycas calocama*	Cuba (Pinar del Río)	Threatened
265.	*Stangeria eriopus*	South Africa (Eastern Cape, KwaZulu-Natal)	Threatened
266.	*Zamia acuminata*	Costa Rica (San José), Nicaragua, Panama (Coclé, Panamá)	Threatened
267.	*Zamia amazonum*	Brazil (Amazonas), Colombia,	Non-threatened

		(Amazonas, Vaupés), Ecuador (Morona-Santiago, Napo, Sucumbíos), Peru (Loreto), S Venezuela	
268.	*Zamia amblyphyllidia*	Cuba, Jamaica, Puerto Rico	Threatened
269.	*Zamia amplifola*	Colombia (Valle del Cauca)	Threatened
270.	*Zamia boliviana*	North Bolivia, Brazil	Non-threatened
271.	*Zamia chigua*	Colombia (Chocó, Valle del Cauca)	Non-threatened
272.	*Zamia cremnophila*	Mexico (Tabasco)	Threatened
273.	*Zamia cunaria*	Panama (Colón, Panamá, Kuna de Wargandi, Kuna Yala)	Threatened
274.	*Zamia decumbens*	Belize (Cayo, Stann Creek, Toledo)	Threatened
275.	*Zamia disodon*	Colombia (Antioquia)	Threatened
276.	*Zamia dressleri*	Panama (Colón, Kuna Yala)	Threatened
277.	*Zamia elegantissima*	Panama (Colón, Panama)	Threatened
278.	*Zamia encephalartoides*	Colombia (Santander)	Threatened
279.	*Zamia fairchildiana*	Costa Rica (Puntarenas, San José), Panama (Chiriquí)	Non-threatened
280.	*Zamia fischeri*	Mexico (Hidalgo, Querétaro, San Luis Potosí, Tamaulipas)	Threatened
281.	*Zamia furfuracea_A*	Mexico (Veracruz)	Threatened
282.	*Zamia furfuracea_B*	Mexico (Veracruz)	Threatened
283.	*Zamia gentryi*	Ecuador (Carchi, Esmeraldas)	Threatened
284.	*Zamia gomeziana*	Costa Rica (Limón)	Threatened
285.	*Zamia hamannii*	Panama (Bocas del Toro)	Threatened

286.	*Zamia herrerae*	El Salvador (Sonsonate), Guatemala (Quetzaltenango Retalhuleu, Santa Rosa, Suchitepéquez), Mexico (Chiapas)	Threatened
287.	*Zamia hymenophyllidia*	Colombia (Amazonas), Peru (Loreto)	Threatened
288.	*Zamia imperialis*	Panama (Coclé, Colón, Panamá, Veraguas)	Threatened
289.	*Zamia incognita*	Colombia (Antioquia, Boyacá, Santander)	Threatened
290.	*Zamia inermis*	Mexico (Veracruz)	Threatened
291.	*Zamia integrifolia*	Bahamas, Cayman Islands, Cuba, United States (Florida, Georgia)	Non-threatened
292.	*Zamia ipetiensis*	Panama (Panamá, Kuna Yala)	Threatened
293.	*Zamia katzeriana*	Mexico (Chiapas, Tabasco, Veracruz)	Threatened
294.	*Zamia kickxii*	Cuba (W Cuba, Isla de la Juventud)	Threatened
295.	*Zamia lacandona*	Mexico (Chiapas)	Threatened
296.	*Zamia lawsoniana*	Mexico (Chiapas, Hidalgo, Oaxaca, Tabasco, Tamaulipas, Veracruz)	Non-threatened
297.	*Zamia lecointei*	Brazil (Pará), Colombia (Amazonas), Venezuela (Amazonas)	Non-threatened
298.	*Zamia lindenii*	Panama (Bocas del Toro, Chiriquí)	Non-threatened
299.	*Zamia lindleyi*	Panama (Bocas del Toro,	Threatened

		Chiriquí)	
300.	*Zamia loddigesii*	Mexico (Chiapas, Hidalgo, Oaxaca, Tabasco, Tamaulipas, Veracruz)	Non-threatened
301.	*Zamia lucayana*	Bahamas (Abaco, Long Island)	Threatened
302.	*Zamia macrochiera*	Peru (Loreto)	Threatened
303.	*Zamia manicata*	Colombia (Antioquia, Chocó), Panama (Darién)	Non-threatened
304.	*Zamia meermanii*	Belize (Belize, Cayo)	Threatened
305.	*Zamia melanorrhachis*	Colombia (Antioquia, Córdoba, Santander)	Threatened
306.	*Zamia montana*	Colombia (Antioquia, Risaralda)	Threatened
307.	*Zamia monticola*	Guatemala (Alta Verapaz)	Threatened
308.	*Zamia muricata*	Colombia (La Guajira, Meta), Venezuela (Carabobo, Falcón, Guárico, Lara, Miranda, Yaracuy)	Non-threatened
309.	*Zamia nesophila*	Panama (Bocas del Toro)	Threatened
310.	*Zamia neurophyllidia*	Costa Rica, S Nicaragua, Panama (Bocas del Toro)	Threatened
311.	*Zamia obliqua*	Colombia (Antioquia, Chocó, Valle del Cauca), Costa Rica (Puntarenas), Panama (Darién, Panamá)	Non-threatened
312.	*Zamia onan-reyesii*	Honduras (Cortés)	Threatened
313.	*Zamia oreillyi*	Honduras (Atlántida)	Threatened
314.	*Zamia paucijuga*	Mexico (Colima, Guerrero, Jalisco, Michoacán, Nayarit, Oaxaca)	Non-threatened

315.	*Zamia picta*	Belize (Toledo), Guatemala (Alta Verapaz, Izabal), Mexico (Chiapas)	Threatened
316.	*Zamia poeppigiana*	Brazil (Acre), Peru (Amazonas, Huánuco, Loreto, Pasco, San Martin, Ucayali)	Non-threatened
317.	*Zamia portoricensis*	W Puerto Rico	Threatened
318.	*Zamia prasina*	Belize (Belize, Cayo, Orange Walk, Stann Creek, Toledo), Guatemala (Petén), Mexico (Campeche, Chiapas, Tabasco, Quintana Roo, Yucatán)	Threatened
319.	*Zamia pseudomonticola*	Costa Rica (Puntarenas), Panama (Chiriquí)	Non-threatened
320.	*Zamia pseudoparasitica*	Panama (Bocas del Toro, Coclé, Colón, Veraguas)	Non-threatened
321.	*Zamia pumila*	Cuba, Dominican Republic, Puerto Rico	Non-threatened
322.	*Zamia purpurea*	Mexico (Oaxaca, Veracruz)	Threatened
323.	*Zamia pygmaea*	Cuba (W Cuba, Isla de la Juventud)	Threatened
324.	*Zamia pyrophylla*	Colombia (Chocó)	Threatened
325.	*Zamia restrepoi*	Colombia (Córdoba)	Threatened
326.	*Zamia roezlii*	Colombia (Amazonas, Chocó, Nariño, Valle del Cauca), Ecuador (Esmeraldas, Imbabura)	Non-threatened
327.	*Zamia sandovalii*	Honduras (Atlántida)	Non-threatened
328.	*Zamia skinneri*	Panama (Bocas del Toro)	Threatened
329.	*Zamia soconuscensis*	Mexico (Chiapas)	Threatened

330.	*Zamia spartea*	Mexico (Oaxaca)	Threatened
331.	*Zamia standleyi*	Guatemala (Izabal), Honduras (Atlántida, Colón, Cortés, Olancho, Santa Barbara, Yoro)	Threatened
332.	*Zamia stricta*	Cuba (Oriente)	Threatened
333.	*Zamia tolimensis*	Colombia (Tolima)	Threatened
334.	*Zamia tuerckheimii*	Guatemala (Alta Verapaz	Non-threatened
335.	*Zamia ulei*	W Brazil, Colombia (Amazonas, Guainía), Ecuador (Napo, Pastaza), Peru (Loreto, Madre de Dios)	Non-threatened
336.	*Zamia urep*	Peru (Huánuco)	Threatened
337.	*Zamia variegate*	Belize (Toledo), Guatemala (Alta Verapaz, Izabal), Mexico (Chiapas)	Threatened
338.	*Zamia vazquezii*	Mexico (Veracruz)	Threatened
339.	*Zamia wallisii*	Colombia (Antioquia)	Threatened

Appendix 2

ED score of all cycad species. Species are listed in following the decreasing order of ED values. Global endangerment was measured by following IUCN threat categories: Least concern (LC), near threatened (NT), Vulnerable (VU), Endangered (EN) and Critically endangered (CR). Geographic parameters are spatial distribution range and Maximum altitude. Number of threats (Diversity of threat), Threat status (Threatened vs. non-threatened), Maximum height, Maximum diameter as well as Generation time are all well represented including their values respectively.

Ranking	**Species**	**Global Endangerment**	**Number of threats**	**ED score (MY)**	**Range (km^2)**	**Maximum altitude (m above the sea)**	**Maximum height (m)**	**Generation time (Y)**	**Maximum diameter (cm)**
1	*Microcycas_calocoma*	CR	3	98.76153	NA	NA	10	100	0.6
2	*Chigua_bernalii*	CR	3	92.77871	NA	150	1.4	NA	1.6
3	*Stangeria_eriopus*	VU	5	86.06692	NA	750	NA	30	NA
4	*Zamia_vazquezii*	CR	1	66.9213	NA	NA	0.3	30	0.1
5	*Cycas_balansae*	NT	2	60.96541	NA	800	NA	40	0.2

6	*Cycas_conferta*	NT	2	60.36198	NA	NA	7	40	0.13
7	*Cycas_taiwaniana*	EN	2	60.36198	NA	1100	3.5	40	0.3
8	*Dioon_caputoi*	EN	2	60.02895	NA	NA	1	500	0.25
9	*Dioon_spinulosum*	EN	2	58.81312	NA	NA	16	500	0.4
10	*Macrozamia_cranei*	EN	1	54.65748	NA	600	NA	60	0.25
11	*Macrozamia_johnsonii*	LC	1	54.65748	222	NA	3	60	0.9
12	*Encephalartos_brevifoliolatus*	EW	1	53.41136	NA	700	2.5	70	0.3
13	*Encephalartos_ngoyanus*	VU	2	53.41136	NA	600	0.3	35	0.2
14	*Zamia_herrerae*	VU	1	52.42318	NA	NA	NA	30	0.1
15	*Encephalartos_gratus*	VU	1	52.39442	NA	900	2.5	70	0.6
16	*Cycas_brachycantha*	NT	0	51.24649	NA	NA	1	40	0.12
17	*Cycas_tropophylla*	NT	0	51.24649	400	NA	1	40	0.15
18	*Bowenia_serrulata*	LC	1	50.14995	NA	150	NA	30	0.25

19	*Bowenia_spectabilis*	LC	1	50.14995	NA	750	NA	30	10
20	*Zamia_neurophyllidia*	VU	1	48.38625	NA	NA	2	30	0.12
21	*Zamia_skinneri*	EN	1	47.67762	6250	NA	2.4	30	0.2
22	*Ceratozamia_morettii*	EN	1	47.26377	10	NA	0.3	45	0.08
23	*Encephalartos_cupidus*	CR	4	47.18981	290	1800	0.75	200	0.3
24	*Encephalartos_dolomiticus*	CR	2	47.18981	0.3	700	2	70	0.4
25	*Encephalartos_inopinus*	CR	2	46.26647	NA	800	3	200	0.25
26	*Macrozamia_humilis*	VU	1	45.99116	NA	600	NA	60	0.28
27	*Cycas_macrocarpa*	VU	1	45.82549	NA	NA	12	40	NA
28	*Encephalartos_turneri*	LC	0	45.29299	NA	1200	3	70	0.8
29	*Zamia_macrochiera*	CR	1	45.24072	NA	NA	NA	30	0.2
30	*Ceratozamia_zoquorum*	CR	2	44.3358	40	NA	0.31	45	0.1047
31	*Lepidozamia_hopei*	LC	0	43.35002	NA	1000	17	100	0.5

32	*Lepidozamia_peroffskyana*	LC	1	43.35002	NA	1000	7	70	0.8
33	*Cycas_ferruginea*	NT	0	43.33355	7215	NA	1.2	40	0.18
34	*Cycas_pranburiensis*	VU	1	43.33355	NA	30	3	40	0.1
35	*Ceratozamia_mixeorum*	EN	2	42.82403	25	NA	1.25	45	0.18
36	*Cycas_szechuanensis*	CR	2	42.39772	NA	NA	2	40	0.25
37	*Zamia_spartea*	CR	1	41.82245	1235	NA	NA	30	0.1
38	*Ceratozamia_microstrobila*	VU	1	41.76929	1000	NA	0.25	45	10
39	*Zamia_cunaria*	VU	1	39.96309	3140	NA	NA	NA	0.1
40	*Ceratozamia_alvarezii*	EN	2	39.5459	16	NA	0.5	45	0.175
41	*Ceratozamia_chimalapensis*	CR	2	39.5459	NA	NA	0.1	NA	0.331
42	*Ceratozamia_fuscoviridis*	CR	3	39.03437	NA	NA	0.36	NA	0.22
43	*Ceratozamia_huastecorum*	CR	0	39.03437	NA	NA	NA	45	NA
44	*Zamia_lacandona*	EN	2	38.76277	3400	NA	0.6	30	0.08

45	*Zamia_loddigesii*	NT	2	38.73882	NA	NA	0.3	30	0.12
46	*Zamia_urep*	CR	1	38.73882	30	NA	0.5	30	0.03
47	*Cycas_fugax*	CR	1	37.99666	NA	200	NA	40	0.12
48	*Cycas_inermis*	VU	2	37.99666	NA	NA	4	40	0.14
49	*Zamia_variegata*	EN	1	36.92315	NA	NA	0.2	30	0.08
50	*Cycas_micholitzii*	VU	1	36.43868	NA	600	NA	40	0.15
51	*Cycas_segmentifida*	VU	1	36.43868	NA	900	0.5	40	0.23
52	*Ceratozamia_hildae*	EN	2	36.39392	NA	NA	0.2	45	0.25
53	*Encephalartos_eugene maraisii*	EN	2	35.18108	NA	100	4	70	0.45
54	*Encephalartos_concinnus*	EN	2	34.9623	58	1500	3	70	0.45
55	*Encephalartos_middleburgensis*	CR	4	34.9623	NA	1400	7	70	0.45
56	*Zamia_hymenophyllidia*	CR	1	34.88073	NA	NA	NA	30	0.04
57	*Zamia_pseudoparasitica*	NT	2	34.88073	NA	NA	1	30	0.15

58	*Zamia_katzeriana*	EN	0	34.87335	NA	NA	NA	30	NA
59	*Ceratozamia_mirandae*	EN	3	34.77023	NA	NA	NA	45	NA
60	*Zamia_imperialis*	CR	2	34.74487	NA	NA	1.1	NA	0.22
61	*Encephalartos_whitelockii*	CR	3	34.44208	NA	1300	4	70	0.4
62	*Encephalartos_nubimontanus*	EW	0	34.26229	NA	1000	2.5	NA	0.4
63	*Encephalartos_lanatus*	NT	2	34.20526	NA	1500	2	70	0.3
64	*Cycas_curranii*	CR	2	34.0329	NA	NA	3	40	NA
65	*Cycas_hainanensis*	EN	2	34.0329	NA	1200	3.5	40	0.3
66	*Cycas_indicaA.*	DD	1	33.75955	NA	NA	4	40	0.23
67	*Ceratozamia_decumbens*	CR	2	33.73552	NA	NA	0.2	NA	14
68	*Ceratozamia_santillanii*	CR	0	33.73552	NA	NA	NA	45	NA
69	*Zamia_furfuracea_A*	EN	2	33.70254	630	NA	NA	30	0.2
70	*Zamia_lawsoniana*	NT	2	33.70254	NA	NA	NA	30	NA

71	*Zamia_prasina*	CR	1	33.45521	NA	NA	0.3	30	0.1
72	*Macrozamia_elegans*	EN	2	33.38726	112	150	NA	60	0.3
73	*Macrozamia_machinii*	VU	1	33.38726	460	460	NA	60	0.3
74	*Cycas_arnhemica*	LC	1	32.74662	NA	NA	2.5	40	0.2
75	*Zamia_integrifolia*	NT	2	32.54882	NA	NA	1.3	30	0.06
76	*Zamia_acuminata*	VU	1	32.43504	NA	NA	0.4	30	0.08
77	*Macrozamia_fawcettii*	NT	1	32.3706	5500	550	NA	60	0.2
78	*Macrozamia_conferta*	VU	1	32.28496	423	750	NA	60	0.3
79	*Macrozamia_crassifolia*	VU	0	32.28496	160	420	NA	60	0.2
80	*Zamia_monticola*	CR	1	31.85847	NA	NA	0.3	30	0.2
81	*Cycas_couttsiana*	NT	0	31.82362	NA	700	7	40	0.2
82	*Zamia_onan-reyesii*	CR	2	31.72165	NA	NA	NA	NA	NA
83	*Zamia_tolimensis*	CR	2	31.59701	NA	NA	4	NA	0.3

84	*Zamia_nesophila*	CR	2	31.01836	NA	NA	2.8	NA	0.24
85	*Zamia_standleyi*	VU	0	31.01836	NA	NA	NA	30	0.12
86	*Encephalartos_longifolius*	NT	1	30.9371	NA	700	4	70	0.4
87	*Encephalartos_woodii*	EW	1	30.9371	NA	NA	6	NA	0.6
88	*Encephalartos_delucanus*	EN	3	30.92973	NA	1500	0.12	70	0.2
89	*Encephalartos_poggei*	LC	1	30.92973	NA	1000	2	70	0.3
90	*Cycas_semota*	NT	1	30.74311	NA	NA	5	40	NA
91	*Ceratozamia_becerrae*	EN	2	30.23118	1000	NA	0.31	45	0.1047
92	*Ceratozamia_zaragozae*	CR	1	30.23118	45	NA	NA	45	NA
93	*Cycas_brunnea*	NT	1	30.05926	NA	NA	5	40	0.23
94	*Cycas_panzhihuaensis*	VU	3	30.05926	14500	2000	3	40	0.2
95	*Cycas_collina*	VU	2	29.82684	20000	900	NA	40	0.14
96	*Cycas_simplicipinna*	NT	1	29.82684	NA	1300	NA	40	0.14

97	*Macrozamia_fraseri*	LC	0	29.77538	NA	NA	3	60	0.7
98	*Cycas_armstrongii*	VU	2	29.42157	NA	NA	6	40	0.11
99	*Zamia_hamannii*	CR	2	29.18057	NA	NA	2.4	NA	0.2
100	*Zamia_manicata*	NT	1	29.18057	NA	NA	NA	30	0.05
101	*Cycas_elephantipes*	EN	1	29.1319	NA	NA	3	40	0.2
102	*Cycas_pruinosa*	LC	0	29.1319	NA	NA	2.5	40	0.35
103	*Cycas_changjiangensis*	EN	2	29.03681	NA	800	2.5	40	0.2
104	*Cycas_javana*	EN	1	28.4363	NA	NA	4	40	0.2
105	*Cycas_vespertilio*	NT	1	28.4363	NA	NA	3	40	NA
106	*Encephalartos_equatorialis*	CR	3	28.26662	NA	1500	6	70	0.6
107	*Encephalartos_umbeluziensis*	EN	1	28.26662	336	120	0.3	35	0.25
108	*Zamia_angustifolia*	VU	1	28.15189	9000	NA	NA	30	NA
109	*Zamia_decumbens*	CR	2	28.15189	NA	NA	80	NA	0.11

110	*Cycas_hongheensis*	CR	2	28.09396	NA	600	3	40	0.15
111	*Cycas_orientis*	LC	1	28.09396	NA	NA	7	40	0.14
112	*Macrozamia_dyeri*	LC	1	28.07962	NA	NA	3	60	1.2
113	*Zamia_dressleri*	EN	1	28.07089	2530	NA	NA	30	0.05
114	*Zamia_wallisii*	CR	3	28.07089	NA	NA	NA	30	0.05
115	*Zamia_lucayana*	EN	1	27.68497	13	NA	NA	30	NA
116	*Zamia_tuerckheimii*	NT	1	27.68497	NA	NA	3	30	NA
117	*Zamia_chigua*	NT	0	27.525	NA	NA	2	30	0.15
118	*Zamia_meermanii*	EN	3	27.525	NA	NA	NA	NA	NA
119	*Macrozamia_mountperriensis*	LC	1	27.25841	NA	400	NA	60	0.4
120	*Encephalartos_ituriensis*	NT	1	27.00078	NA	1200	6	70	0.5
121	*Encephalartos_marunguensis*	VU	2	27.00078	7500	1700	0.4	70	0.15
122	*Zamia_boliviana*	NT	0	26.80184	NA	NA	NA	30	0.1
123	*Ceratozamia_brevifrons*	DD	2	26.68981	NA	NA	0.28	45	0.19

124	*Encephalartos_chimanimaniensis*	EN	1	26.60507	NA	1100	1.8	70	0.45
125	*Zamia_inermis*	CR	4	26.59268	NA	NA	1.5	30	0.25
126	*Macrozamia_douglasii*	LC	0	26.54739	NA	150	0.6	60	0.7
127	*Macrozamia_lucida*	LC	0	26.54739	NA	600	NA	60	0.2
128	*Zamia_ipetiensis*	EN	1	26.5222	50	NA	NA	30	0.1
129	*Zamia_gentryi*	CR	1	26.08393	5	NA	1.5	30	0.15
130	*Zamia_paucijuga*	NT	0	26.08393	NA	NA	NA	30	0.08
131	*Cycas_condaoensis*	VU	0	26.07318	20	NA	2.5	40	0.17
132	*Ceratozamia_vovidesii*	VU	2	25.92663	NA	1700	NA	45	NA
133	*Zamia_picta*	EN	1	25.883	NA	NA	NA	30	NA
134	*Zamia_fischeri*	EN	1	25.79944	2770	NA	NA	30	0.08
135	*Zamia_sandovalii*	NT	0	25.79944	NA	NA	NA	30	NA
136	*Zamia_pumila*	NT	0	25.78335	NA	NA	NA	30	0.25
137	*Cycas_nitida*	NT	1	25.681	NA	NA	NA	NA	NA

				27					
138	*Cycas_taitungensis*	EN	2	25.68127	65	900	0.06	40	0.3
139	*Zamia_encephalartoides*	VU	1	25.66209	266	NA	2	30	0.25
140	*Macrozamia_spiralis*	EN	0	25.61488	NA	NA	NA	60	0.2
141	*Cycas_beddomei*	EN	4	25.56325	388	900	2	40	0.23
142	*Cycas_circinalis*	EN	4	25.56325	NA	1000	7	40	0.27
143	*Ceratozamia_kuesteriana*	CR	2	25.5329	NA	NA	NA	45	NA
144	*Ceratozamia_sabatoi*	EN	2	25.5329	NA	NA	0.5	45	0.175
145	*Zamia_gomeziana*	VU	2	25.3669	NA	NA	NA	NA	NA
146	*Zamia_pyrophylla*	CR	1	25.3669	NA	NA	NA	NA	0.1
147	*Ceratozamia_matudae*	EN	2	24.96245	5000	NA	0.5	45	0.175
148	*Cycas_candida*	EN	1	24.9318	55	NA	NA	40	NA
149	*Encephalartos_pterogononus*	CR	2	24.90164	35	1000	1.5	70	0.4
150	*Encephalartos_mackenz*	NT	1	24.782	NA	2000	2.5	70	NA

	iei			82					
151	*Macrozamia_glaucophylla*	LC	0	24.76862	NA	NA	NA	60	0.4
152	*Macrozamia_secunda*	VU	0	24.76862	NA	NA	NA	60	0.15
153	*Cycas_bougainvilleana*	NT	0	24.69741	NA	NA	5	40	NA
154	*Dioon_califanoi*	EN	3	24.654	126	NA	3	500	0.3
155	*Macrozamia_diplomera*	LC	0	24.60612	NA	500	NA	60	0.4
156	*Zamia_fairchildiana*	NT	0	24.51522	NA	NA	1	30	0.15
157	*Cycas_hoabinhensis*	EN	1	24.43046	NA	150	0.6	40	0.08
158	*Cycas_petraea*	NT	0	24.43046	60	NA	6	40	0.2
159	*Encephalartos_humilis*	VU	2	24.40141	NA	NA	0.5	NA	0.18
160	*Encephalartos_laevifolius*	CR	4	24.40141	NA	1800	4	70	0.35
161	*Zamia_pygmaea*	CR	0	24.13965	NA	NA	0.02	30	0.04
162	*Zamia_ulei*	NT	1	24.13965	NA	NA	1	30	0.06
163	*Zamia_montana*	CR	2	23.94414	NA	NA	1.5	30	0.2

164	*Zamia_purpurea*	CR	1	23.94414	NA	NA	0.5	30	0.04
165	*Encephalartos_arenarius*	EN	2	23.34009	140	1500	1	70	0.3
166	*Encephalartos_paucidentatis*	VU	2	23.34009	424	1500	7	70	0.7
167	*Cycas_revoluta*	LC	2	23.2936	NA	300	2	40	0.2
168	*Cycas_terryana*	VU	1	23.2936	NA	NA	NA	40	NA
169	*Macrozamia_longispina*	NT	0	23.27557	50	700	0.3	60	0.3
170	*Encephalartos_hirsutus*	CR	1	23.22916	NA	1000	4	70	0.4
171	*Encephalartos_transvenosus*	LC	2	23.22916	NA	1500	13	70	0.5
172	*Zamia_lecointei*	NT	0	22.97657	NA	NA	NA	30	0.1
173	*Ceratozamia_miqueliana*	CR	2	22.91372	NA	NA	0.31	45	0.1047
174	*Dioon_mejiae*	LC	2	22.89612	NA	NA	1	500	0.25
175	*Encephalartos_bubalinus*	NT	1	22.75749	NA	900	2	70	0.45
176	*Encephalartos_princeps*	VU	2	22.75749	1870	800	5	70	0.4

177	*Macrozamia_flexuosa*	EN	2	22.74608	NA	NA	NA	60	0.2
178	*Macrozamia_stenomera*	NT	2	22.74608	NA	NA	NA	60	0.25
179	*Cycas_montana*	NT	3	22.60174	NA	NA	1.5	NA	0.35
180	*Dioon_merolae*	VU	3	22.43078	NA	NA	3	500	0.4
181	*Dioon_sonorense*	EN	3	22.43078	NA	NA	NA	500	NA
182	*Ceratozamia_norstogii*	EN	1	22.39375	1100	NA	0.5	45	0.175
183	*Encephalartos_latifrons*	CR	3	22.23855	NA	600	3	100	NA
184	*Zamia_pseudomonticola*	NT	0	21.7473	NA	NA	0.3	30	0.07
185	*Cycas_seemanii*	VU	1	21.69839	NA	600	10	40	0.2
186	*Cycas_chevalieri*	NT	1	21.68381	NA	NA	1.2	NA	0.18
187	*Zamia_furfuracea_B*	EN	1	21.53129	631	NA	NA	30	0.2
188	*Zamia_soconuscensis*	VU	1	21.53129	NA	NA	0.5	30	0.25
189	*Zamia_lindenii*	NT	2	21.50499	NA	NA	4	30	0.3

190	*Cycas_papuana*	NT	1	21.47898	NA	NA	2.8	40	NA
191	*Cycas_elongata*	EN	3	21.47247	NA	200	5	40	0.2
192	*Dioon_holmgrenii*	EN	2	21.43385	NA	NA	6	500	0.4
193	*Dioon_purpusii*	VU	0	21.43385	NA	1500	5	500	0.4
194	*fridericiguilielmi"*	NT	2	21.40559	NA	600	4	70	0.6
195	*Encephalartos_natalensis*	NT	2	21.40559	NA	1200	6.5	70	0.4
196	*Cycas_cairnsiana*	VU	1	21.22965	NA	500	5	40	0.16
197	*Zamia_amplifolia*	CR	1	21.18936	NA	NA	2.5	30	NA
198	*Zamia_muricata*	NT	0	21.18936	NA	NA	0.15	30	0.08
199	*Cycas_miquellii*	LC	2	21.02826	NA	300	NA	NA	NA
200	*Encephalartos_aplanatus*	VU	2	21.02188	NA	1400	NA	35	NA
201	*Encephalartos_lehmannii*	NT	3	21.01598	NA	1000	3	200	0.45
202	*Dioon_argenteum*	VU	1	20.82433	350	1600	3	500	0.32

203	*Dioon_rzedowskii*	EN	1	20.82433	25	NA	5	500	0.4
204	*Cycas_silvestris*	VU	0	20.74771	NA	NA	0.04	40	0.15
205	*Ceratozamia_latifolia*	EN	2	20.70881	NA	NA	0.2	45	0.1
206	*Ceratozamia_robusta*	EN	3	20.70881	NA	NA	2	45	0.3
207	*Cycas_cupida*	VU	2	20.61617	60	NA	NA	40	NA
208	*Cycas_tanqingii*	NT	1	20.61617	80	800	2	40	0.3
209	*Dioon_edule*	NT	2	20.61607	NA	NA	3	700	0.3
210	*Dioon_stevensonii*	CR	0	20.61607	NA	NA	NA	NA	NA
211	*Cycas_annaikalensis*	CR	1	20.23621	NA	940	5	40	0.61
212	*Cycas_lindstromii*	EN	2	20.23621	4280	30	NA	40	0.08
213	*Cycas_zambalensis*	CR	4	20.19838	NA	NA	3	40	NA
214	*Encephalartos_lebomboensis*	EN	3	20.10179	NA	1000	5	70	0.3
215	*Encephalartos_senticosus*	VU	1	20.10179	NA	800	4	70	0.3

216	*Ceratozamia_euryphyllidia*	CR	1	20.08057	NA	NA	0.31	45	0.1047
217	*Ceratozamia_mexicana*	VU	3	20.08057	NA	NA	1	45	0.2
218	*Ceratozamia_hondurensis*	CR	5	19.85266	NA	NA	NA	45	NA
219	*Ceratozamia_whitelockiana*	EN	2	19.85266	NA	NA	0.3	45	0.18
220	*Encephalartos_schmitzii*	VU	3	19.82233	NA	1400	0.3	500	0.2
221	*Encephalartos_ferox*	NT	2	19.8147	NA	1400	2	70	0.3
222	*Encephalartos_ghellincki*	VU	2	19.8147	NA	2400	3	70	0.4
223	*Cycas_nongnoochiae*	VU	2	19.79711	NA	100	5	NA	0.15
224	*Cycas_tuckeri*	VU	2	19.79711	15	NA	5	40	NA
225	*Zamia_elegantissima*	EN	1	19.60963	100	NA	NA	30	NA
226	*Zamia_obliqua*	NT	0	19.60963	NA	NA	5	30	0.12
227	*Cycas_pachypoda*	CR	2	19.21076	NA	NA	1.5	40	0.17
228	*Cycas_campestris*	NT	2	19.20191	20000	NA	2.5	40	0.2

229	*Cycas_saxatilis*	VU	1	19.20191	NA	NA	4	40	NA
230	*Encephalartos_aemulans*	CR	2	19.12329	295	600	3	70	0.35
231	*Encephalartos_villosus*	LC	2	19.12329	NA	600	0.3	35	0.2
232	*Zamia_poeppigiana*	NT	0	19.07345	NA	NA	3	30	0.3
233	*Zamia_lindleyi*	DD	1	19.07345	NA	NA	3	30	0.3
234	*Cycas_wadei*	CR	3	19.06555	NA	50	5	40	0.2
235	*Cycas_dolichophylla*	NT	0	18.87451	NA	NA	1.5	40	0.3
236	*Dioon_angustifolium*	VU	0	18.87281	NA	NA	NA	500	NA
237	*Dioon_tomasellii*	VU	2	18.87281	NA	1850	1	500	NA
238	*Zamia_amazonum*	NT	0	18.789	NA	NA	2.5	30	0.08
239	*Cycas_bifida*	VU	2	18.72094	NA	300	NA	40	NA
240	*Cycas_thouarsii*	LC	2	18.7099	NA	200	4	40	0.1
241	*Macrozamia_pauliguilielmi*	EN	2	18.55799	NA	25	NA	60	0.2
242	*Macrozamia_polymorph*	LC	0	18.557	NA	NA	NA	60	0.25

	a			99					
243	*Cycas_megacarpa*	VU	1	18.53765	NA	300	6	40	0.14
244	*Cycas_platyphylla*	EN	1	18.53765	NA	750	4	40	0.15
245	*Cycas_multipinnata*	EN	2	18.43632	27040	1300	NA	40	0.25
246	*Cycas_aculeata*	VU	1	18.227	10	NA	NA	30	0.18
247	*Cycas_canalis*	LC	3	18.227	NA	NA	5	40	0.14
248	*Encephalartos_heenanii*	CR	4	17.77268	300	1750	4	70	0.35
249	*Encephalartos_msinganus*	CR	3	17.77268	10	1200	3	70	0.35
250	*Cycas_badensis*	NT	1	17.56073	NA	NA	8	40	NA
251	*Cycas_pectinata_B*	VU	1	17.56073	NA	1300	12	40	0.2
252	*Cycas_media_media*	LC	2	17.49625	NA	860	6	40	0.18
253	*Encephalartos_laurentianus*	NT	1	17.44729	NA	550	15	70	1
254	*Macrozamia_riedlei*	LC	0	17.26147	NA	NA	0.3	60	0.4
255	*Cycas_cantafolia*	CR	3	17.23081	NA	NA	NA	NA	NA
256	*Cycas_sphaerica*	DD	1	17.230	NA	1000	5	40	0.27

				81					
257	*Encephalartos_cerinus*	CR	2	17.17823	NA	900	0.3	35	0.25
258	*Zamia_oreillyi*	VU	0	17.15522	NA	NA	NA	30	NA
259	*Zamia_roezlii*	NT	1	17.15522	NA	NA	7	30	NA
260	*Cycas_calcicola*	LC	3	17.0605	NA	155	5	40	0.22
261	*Encephalartos_manikensis*	VU	1	16.90228	NA	1400	1.5	70	0.3
262	*Encephalartos_hildebrandtii*	NT	3	16.6309	NA	600	6	70	0.6
263	*Zamia_portoricensis*	EN	1	16.55332	220	NA	NA	30	0.15
264	*Zamia_stricta*	VU	0	16.55332	25	NA	NA	30	NA
265	*Cycas_arenicola*	NT	0	16.41264	NA	NA	2.5	40	0.2
266	*Cycas_desolata*	VU	0	16.41264	NA	550	7	40	0.25
267	*Zamia_cremnophila*	EN	0	16.38093	53	NA	25	30	0.09
268	*Zamia_melanorrhachis*	EN	1	16.38093	NA	NA	NA	30	0.08
269	*Zamia_disodon*	CR	1	16.345	NA	NA	NA	30	0.08

				63					
270	*Zamia_restrepoi*	CR	3	16.34563	NA	150	NA	30	NA
271	*Macrozamia_moorei*	NT	1	16.16684	NA	500	7	60	0.8
272	*Cycas_maconochiei*	LC	2	15.93741	NA	40	7	40	0.15
273	*Cycas_xipholepis*	LC	0	15.93741	NA	NA	6	40	0.15
274	*Cycas_media_ensata*	LC	2	15.78573	NA	860	6	40	0.18
275	*Cycas_yorkiana*	NT	2	15.78573	11530	NA	4	40	NA
276	*Macrozamia_communis*	LC	1	15.78572	NA	300	1.5	60	0.9
277	*Macrozamia_platyrhachis*	VU	2	15.78572	NA	NA	NA	60	0.6
278	*Cycas_apoa*	NT	1	15.77197	NA	NA	2.5	40	NA
279	*Macrozamia_plurinervia*	EN	4	15.7715	NA	NA	NA	60	0.3
280	*Cycas_angulata*	LC	0	15.77084	NA	30	12	NA	0.25
281	*Cycas_tansachana*	CR	2	15.77084	10	400	5	40	0.18
282	*Encephalartos_barteri*	VU	3	15.628	NA	2150	2.6	70	0.6

				78					
283	*Macrozamia_heteromera*	LC	1	15.2723	NA	200	NA	60	0.9
284	*Macrozamia_concinna*	LC	1	15.18301	NA	1100	NA	60	0.15
285	*Macrozamia_occidua*	VU	1	15.18301	10	1000	NA	60	0.2
286	*Macrozamia_cardiacensis*	VU	0	15.18195	14	640	0.4	60	0.4
287	*Macrozamia_serpentine*	NT	0	15.18195	850	NA	NA	60	NA
288	*Macrozamia_parcifolia*	VU	3	15.17074	NA	220	NA	60	0.2
289	*Macrozamia_viridis*	EN	2	15.17074	1000	NA	NA	60	0.2
290	*Macrozamia_macdonnelli*	LC	2	15.01719	NA	NA	3	60	0.8
291	*Cycas_basaltica*	LC	1	14.90585	NA	260	4	40	0.23
292	*Cycas_ophiolitica*	VU	3	14.90585	NA	250	7	40	0.2
293	*Cycas_chamaoensis*	CR	0	14.78945	NA	NA	10	40	0.28
294	*Zamia_incognita*	VU	2	14.74109	NA	NA	NA	NA	NA
295	*Zamia_amblyphyllidia*	VU	2	14.688	NA	NA	NA	30	0.2

				17					
296	*Zamia_kickxii*	CR	0	14.68817	NA	NA	NA	30	NA
297	*Cycas_lane-poolei*	LC	0	14.37567	NA	370	8	40	0.15
298	*Cycas_rumphii*	NT	1	14.37567	NA	200	10	40	0.2
299	*Cycas_lacrimans*	EN	0	14.358	NA	NA	2	NA	NA
300	*Cycas_nathorstii*	VU	2	14.358	NA	300	4.5	40	0.2
301	*Cycas_riuminiana*	EN	1	14.32454	NA	800	NA	40	NA
302	*Encephalartos_caffer*	NT	2	14.30221	NA	1000	0.4	35	0.25
303	*Cycas_scratchleyana*	NT	0	14.13015	NA	900	7	40	0.2
304	*Cycas_sexseminifera*	VU	1	14.11838	NA	NA	0.6	40	0.15
305	*Cycas_sundaica*	LC	3	14.11838	NA	NA	0.05	40	0.35
306	*Macrozamia_montana*	LC	0	13.9143	NA	NA	0.6	60	0.45
307	*Macrozamia_reducta*	LC	0	13.9143	NA	NA	0.4	60	0.4
308	*Encephalartos_horridus*	EN	2	13.90459	NA	400	0.3	200	0.3
309	*Encephalartos_trispinos*	VU	1	13.904	NA	600	1	NA	0.3

	us			59					
310	*Encephalartos_macrostrobilus*	EN	2	13.7809	50	1400	2.5	70	0.4
311	*Encephalartos_septentrionalis*	NT	3	13.7809	NA	2500	2.5	70	0.75
312	*Cycas_pectinata_A*	VU	1	13.66021	NA	1300	12	40	0.2
313	*Cycas_edentata*	NT	1	13.48673	1000	NA	10	40	0.2
314	*Encephalartos_cycadifolius*	LC	2	13.48624	NA	1950	1.5	500	0.25
315	*Encephalartos_munchii*	CR	2	13.48624	3	1100	1	70	0.35
316	*Encephalartos_tegulaneus*	LC	2	13.12263	NA	2300	10	70	0.6
317	*Macrozamia_fearnsidei*	LC	1	13.06859	NA	600	NA	60	0.35
318	*Macrozamia_miquelii*	LC	0	13.06859	NA	500	NA	60	0.4
319	*Cycas_schumanniana*	NT	2	12.8756	NA	1600	2	40	0.2
320	*Cycas_aenigma*	DD	2	12.8756	NA	NA	4	40	NA
321	*Encephalartos_altensteinii*	VU	3	12.85207	450	200	7	70	0.35
322	*Encephalartos_dyerianu*	CR	2	12.852	5	1000	4	70	0.6

	s			07					
323	*Cycas_litoralis*	NT	1	12.58177	1000	NA	NA	40	NA
324	*Encephalartos_relictus*	EW	1	12.56742	NA	600	NA	NA	NA
325	*Encephalartos_schaijesii*	VU	2	12.56742	NA	1500	0.25	500	0.33
326	*Macrozamia_lomandroides*	EN	2	12.53673	NA	NA	NA	60	0.17
327	*Macrozamia_macleayi*	LC	0	12.53673	NA	500	0.4	60	0.4
328	*Cycas_chamberlainii*	EN	2	12.51481	NA	800	NA	40	NA
329	*Cycas_shanyaensis*	VU	0	12.51481	10	800	3.1	40	0.25
330	*Encephalartos_kisambo*	EN	3	11.67276	NA	1800	4	70	0.6
331	*Encephalartos_sclavoi*	CR	5	11.67276	NA	2100	1	70	0.35
332	*Cycas_clivicola*	LC	1	11.14557	300000	60	8	40	0.16
333	*Cycas_siamensis*	VU	3	11.14557	NA	300	1.5	40	0.2
334	*Cycas_diannanensis*	VU	0	11.02612	NA	1800	0.03	40	0.35
335	*Cycas_falcata*	VU	0	11.026	1350	NA	5	40	0.3

				12					
336	*Cycas_debaoensis*	CR	3	10.80662	NA	1300	NA	40	0.2
337	*Cycas_guizhouensis*	VU	3	10.80662	NA	1300	1	40	0.15
338	*Cycas_micronesica*	EN	3	10.58724	11250000	NA	12	40	0.25
339	*Cycas_zeylanica*	VU	1	10.58724	NA	50	3.1	40	0.2

Appendix 3

Directed separation with Global goodness-of-fit

AIC: 73.776

BIC: 111.519

Independent.claim	Estimate	Std.error	df	Crit.value	P.value
Diamete_ max ~ altitude_max +….	0.0001	0.0000	32	1.3470	0.1874
Height_max ~ altitude_max +….	-0.0007	0.0007	20	-0.9401	0.3584
Range_km2 ~ ED +….	-1150.8607	932.7109	32	-1.2339	0.2262
Diamete_ max ~ ED +….	0.0160	0.0129	67	1.2420	0.2186
Range_km2 ~ No_threats +….	709.7113	9125.2011	31	0.0778	0.9385
Diamete_ max ~ No_threats +….	-0.0004	0.0223	30	-0.0186	0.9852
Generation_time ~ range_km2 +….	0.0000	0.0000	20	-0.7191	0.4721
Generation_time ~ Diamete_ max +….	-0.3864	1.0150	19	-0.3807	0.7034

Fisher's *C* = 13.776 with *P*-value = 0.615 and on 16 degrees of freedom